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Recommended Development Plan for an Aerial Spray Planning and Analysis System (ASPAS)

A Report by KETRON, Inc.
Under Contract 53-9158-0-6406

USDA Forest Service
Forest Pest Management
2810 Chiles Road
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RECOMMENDED DEVELOPMENT PLAN FOR AN AERIAL SPRAY PLANNING AND ANALYSIS SYSTEM

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EXECUTIVE SUMMARY

This report presents a plan for the development of an Aerial Spray Planning and Analysis System (ASPAS). Recommendations are made for the design of the ASPAS system, and a plan is presented for the research and development which will be required to achieve the desired system.

It is widely recognized that there is a genuine need for an information system to plan and to analyze aerial pesticide applications over forest and rangeland. Many of the specific problems identified by the U.S. Forest Service's Aerial Application Technology Workgroup have been addressed in the ASPAS design.

Several other governmental agencies, including the Animal and Plant Health Inspection Service (APHIS) of USDA and the U.S. Army, are actively engaged in research and development projects aimed at producing better methods and information for aerial spray planning and analysis. The U.S. Forest Service should capitalize on its mutual interest with these other organizations, and take full advantage of opportunities for inter-agency cooperation in the development of ASPAS.

The goal in the development of ASPAS is the construction of a working decision-making <u>system</u> which successfully integrates the numerous interrelated factors involved in planning and conducting an aerial spray program. The rationale behind the ASPAS approach is that more effective aerial spray program planning and decision-making will result in more efficient, biologically effective, cost effective, and environmentally safe programs.

The ASPAS system will be useful not only during the planning stages prior to pesticide application projects, but also during the conduct of the operations and during post-application evaluations. The ASPAS will serve as a means of integrating currently available information into a readily usable format, and it will focus research efforts into areas where the need is greatest, to eliminate weak links. The system will also facilitate the evaluation and testing of new spray equipment and techniques.

The Forest Service Cramer/Barry/Grim (FSCBG) computer program will be used as the point of departure for construction of an ASPAS system. The FSCBG is a system of computerized models for predicting aircraft spray dispersion and deposition above and within forest canopies. It combines a droplet evaporation model, a Gaussian diffusion model for above the canopy and a Monte-Carlo ballistic simulation for canopy penetration.

Improvements and additions to the current system have been identified which will advance its accuracy, scope, and ease of use. A key element which is lacking in the present system is an explicit consideration of the biological effectiveness of predicted pesticide distribution. Measures of effectiveness such as target pest mortality must be provided by the system to give a basis for comparison of application methods.

The development of the ASPAS is to evolve the system through discrete generations, or "MODs". Each evolutionary stage represents a higher level of capability than the previous stage. An overview of the ASPAS evolutionary scheme is shown in Figure A. Currently foreseen uses and capabilities for the ASPAs indicate that development through MOD 3 can be recommended at this time. Operational need and opportunities for further development should be reassessed at the completion of MOD 3. Possible directions for subsequent development are discussed in the report.

The plan for ASPAS evolution has been designed to:

- produce an operational system in a short time,
- enable the system to be used over the whole range of major aerial pesticide application situations, including insecticides and herbicides on common forest types and rangeland,
- produce a very usable system in terms of data input program control, and handling and interpretation of output and,
- create an Aerial Spray Planning and Analysis System designed to produce information of a kind and format which can easily be transferred to field use.

The details of the proposed plan are quite flexible in many respects. The Forest Service will have to consider budgeting limitations and specific opportunities for collaboration with other agencies before finalizing plans for development of ASPAS. These factors will ultimately control the rate of development and the choice of particular tasks undertaken.

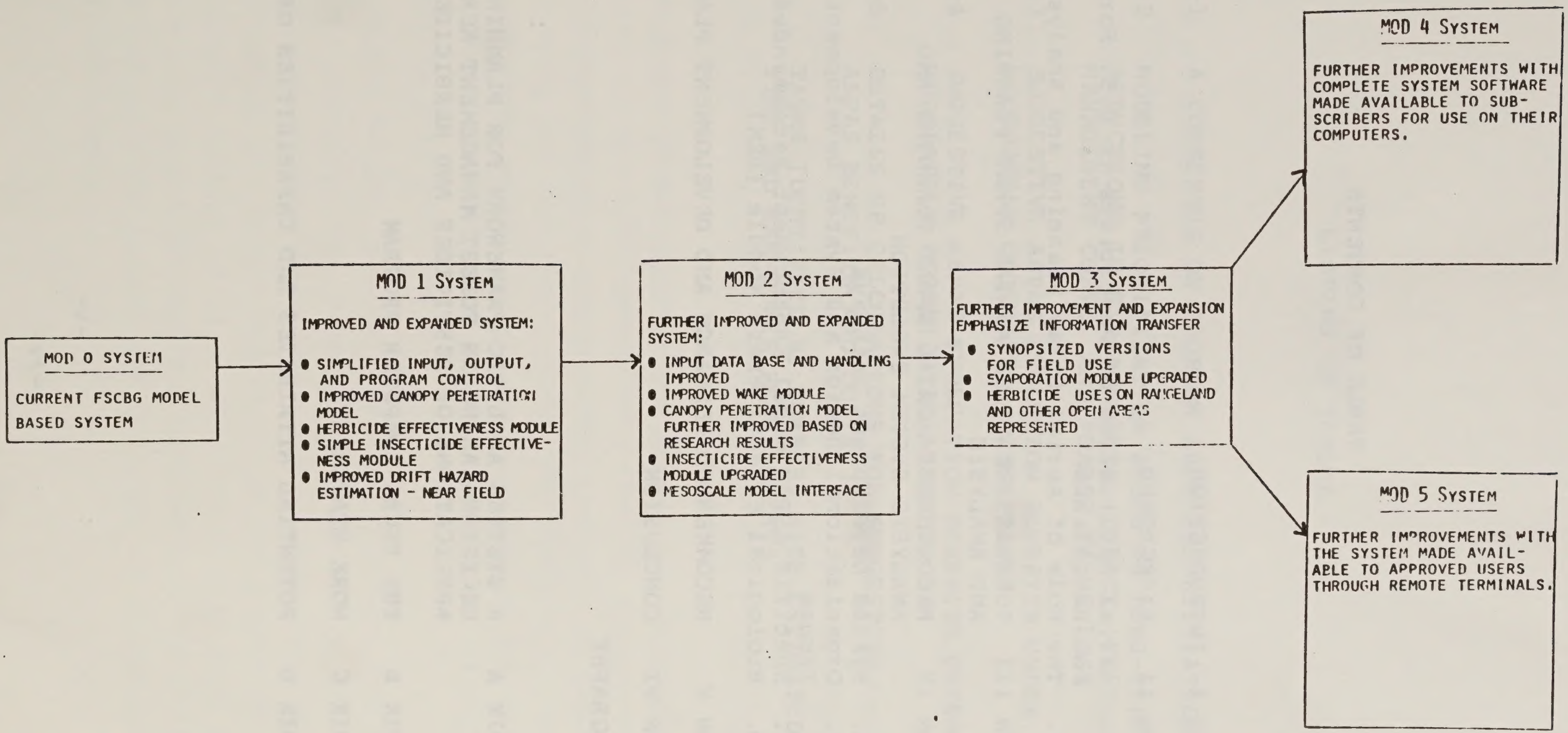

FIGURE A
ASPAS EVOLUTIONARY SCHEME

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INTRODUCTION

The U.S.D. A. Forest Service, Washington Office, Forest Pest Management (WO-FPM) has contracted with Ketron, Inc., a Washington, D.C. based consulting firm specializing in systems analysis, to provide support in the development of an aerial spray planning and analysis system (ASPAS). The contract calls for the generation of ASPAS systems concepts; the recommendation of an ASPAS system (based upon specified criteria, relative costs, and benefits) using the Forest Service Cramer/Barry/Grim model·(FSCBG) as a core; and the development of a research and development plan structured to achieve the desired ASPAS system. This document represents the final report under that contract. This report is expected to serve as a basis for preparing scopes of work for future contracts.

The emphasis of this effort is explicitly on planning. The end objective is the development of a working system which successfully integrates the many factors involved in aerial spray program planning and decision-making. The ASPAS will make possible more effective aerial spray program planning and will result in more efficient, biologically effective, cost effective, and environmentally safe programs.

This report builds upon earlier work regarding the needs for aerial spray analysis and technology, especially that by the Aerial Application Technology Workgroup. Their report entitled "A Problem Analysis: Forest and Range Aerial Pesticide Application Technology" (Ekblad et al., 1979) identified many pertinent problems and some opportunities for improvement. The analysis and plan presented in this report are designed to implement some of those recommendations.

The problems of aerial spray planning and analysis are not unique to the U.S.D.A Forest Service. All major public and private organizations with major forest (or even non-forest) land management responsibilities are potential users of the ASPAS system. Several of these agencies are actively engaged in research and development projects aimed at producing better methods for aerial spray planning and analysis. These organizations include the Animal and Plant Health Inspection Service of USDA which has contracted for the development of a field deployable model for aerial spray analysis, and the governments of Canada and New Brunswick who are cooperating with university researchers to develop models for spray analysis. There is also increased interest and activity within the U.S. Department of Defense. For example, the U.S. Army is currently sponsoring both model develoment and supporting data acquisition projects. The Forest Service should capitalize on its mutual interest with these other organizations, and take full advantage of opportunities for interagency cooperation. Not only could a cooperative effort prevent duplication, but it could produce a more powerful system than separate piecemeal research and development.

The FSCBG Model

ASPAS uses the FSCBG computer program as its core. The FSCBG program is essentially a system of mathematical models which estimate spray drop deposition above and within a forest canopy, and which also estimate nearby off-site drift dosage and peak concentration. The FSCBG model is now constructed in a modular fashion in order to facilitate future enchancements. Figure I-1 is a schematic diagram depicting the modular nature of the FSCBG which currently is operational on the USDA, Fort Collins, Colorado computer system.

Individual FSCBG models deal with:

- aircraft wake effects,
- spray cloud dispersion (using a Gaussian diffusion approach),

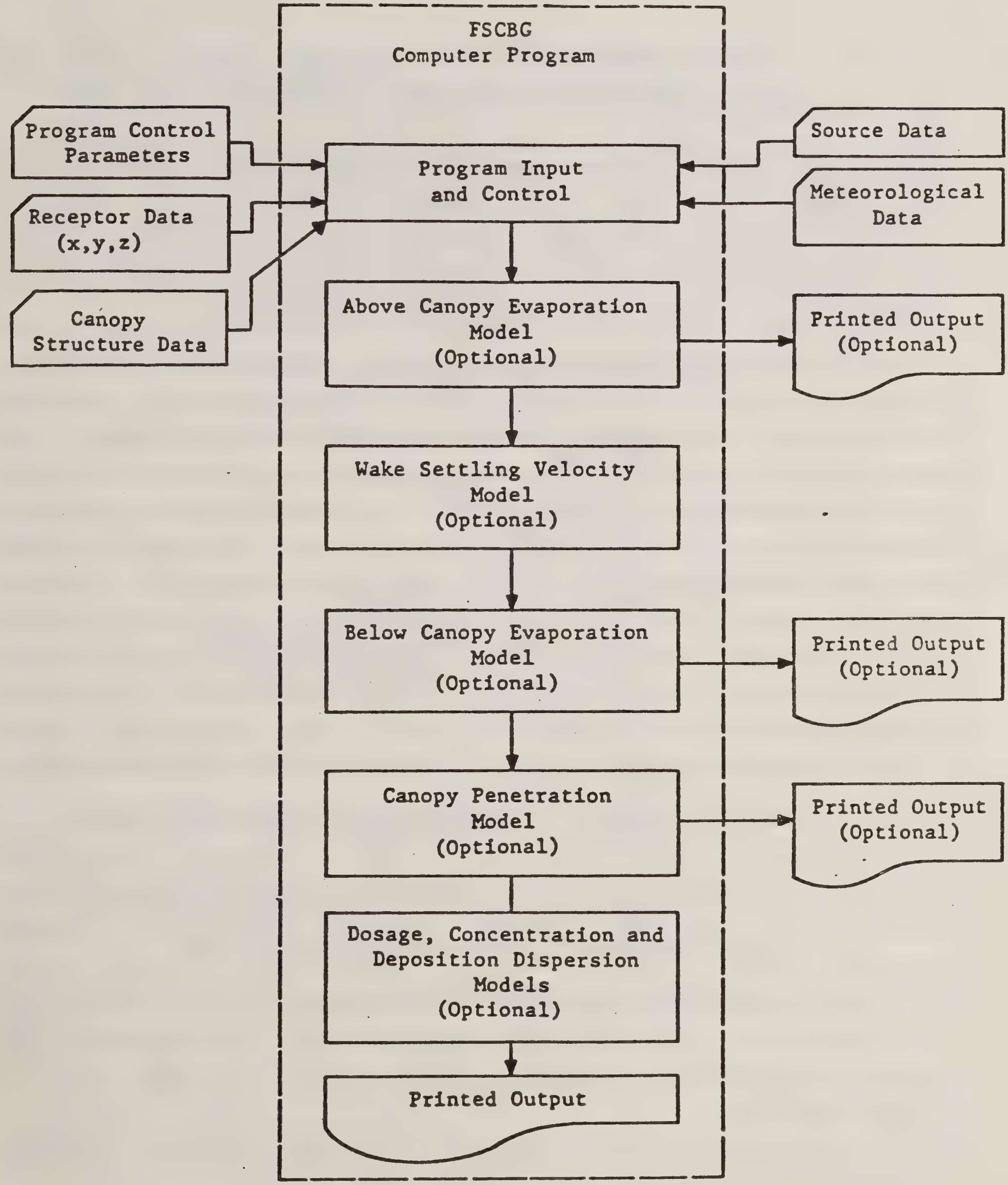

FIGURE I-1

SCHEMATIC DIAGRAM OF THE OPERATIVE FSCBG
COMPUTER PROGRAM OF THE USDA, FOREST SERVICE

Adapted from FSCBG Computer Program Documentation
Report No. 80-11, Oct. 1980.

- droplet evaporation, and
- canopy penetration (using a Monte-Carlo ballistic simulation).

The FSCBG program is designed to calculate spray concentrations and dosages above the forest canopy as well as spray deposition within and below the canopy or over open terrain, resulting from aerial spray releases made by single or multiple swaths. Possible applications of the FSCBG include the following:

(1) Optimization of spray program design and operation with respect to:

- selection of aircraft and spray systems,
- flight altitudes,
- swath widths,
- spray rates,
- droplet distribution,
- scheduling of spray operations,
- atmospheric parameters, and
- pesticide tank mixes.

(2) Evaluation and analysis of field measurements of spray deposition.

(3) Assessment of the environmental risk posed by aerial spray operations.

(4) Prediction of probability of achieving given levels of plant control or insect mortality.

(5) Development of a spray prescription.

To the present time the FSCBG program has been applied only to application of insecticides in coniferous forests, although it could be applied in other forest types and for herbicide applications.

A more detailed discussion of the FSCBG model is included as Appendix B.

The ASPAS System - Approach

The objective as previously stated, is to recommend for development a system (ASPAS) which will enhance spray program planning and the utilization of existing knowledge and experience. In addition to aiding resource managers in planning and conducting spray operations, the system also will assist researchers in prioritizing research needs in the areas of forest protection, aerial spray technology and system modeling. To accomplish these ends, a systems approach has been applied to the problem. Such an approach entails analysis of all factors affecting aerial spray applications and investigating the effect of improved aerial spray program planning within the overall context of pest control management. The analysis has addressed all spray source dispersion and depletion factors as they are affected by physical and chemical forces. It has also investigated the many possible uses of an ASPAS system (such as those listed above) and the specific enhancements and model additions required by such end uses. For example, both the application of the system to other pesticides, most notably herbicides, and applications to hardwood forest and rangeland situations have been considered.

A key element in the analysis has been the study of the biological interface, that is, the use of FSCBG results to estimate the biological effect of the delivered dose on target (and perhaps non-target) species. Such an addition to the system would provide information to support many planning functions (including fiscal planning), as well as providing a measure of effectiveness for various program alternatives.

All potential ASPAS system components have also been considered from the standpoint of relative costs and benefits, prior to final system recommendation. Only those system elements which have been deemed to be sufficiently cost effective have been recommended for development. Those elements which are included in the system have then been prioritized in terms of their relationship to the importance of end uses.

The end products of this analysis are, first, a recommended ASPAS system; second, a research and development plan which has as an end objective the total development of that system; and third, specifications of each new model module to guide future contract action on the part of FPM. It should be noted that the ASPAS system will not be a static collection of mathematical models, but rather a dynamic, flexible system which not only reflects the state of the art, but which allows a furthering of that state, and incorporates advances accordingly.

Organization of the Report

The next section is a background discussion concerning aerial applications of pesticides to forest and rangelands of the United States, and the role of aerial spray planning and analysis. Section III discusses some perceived opportunities for improvement in aerial spray planning and the magnitude of resulting benefits. Section IV presents overall design considerations and specific recommendations for enhancements to the system, with special consideration being given to the biological interface. A plan for implementation of the recommended research and development is described in Section V, along with timing and cost implications. Section VI contains concluding remarks. Appendices present supporting discussions on planning and decision-making in forest pest management, and the FSCBG model, as well as suggested work statements for ASPAS model improvements through MOD 2.

SECTION II
BACKGROUND

A. Aerial Application of Pesticides to U.S. Forest and Rangelands

The objective of this background discussion is not to provide a detailed history of aerial application of pesticides in the U.S. Instead, the intent here is simply to provide information which will enable the reader to place the development of an ASPAS system within a historical and operational perspective. Aerial spraying for the control of forest pests began roughly sixty years ago, however, it was not until the post World War II era that widespread aerial applications became possible. For a large portion of this period the bulk of insect control operations utilized the organochlorine DDT, while herbicide treatments generally centered on the use of 2,4-D, Silvex, and 2,4,5-T. Although the chemicals used since have changed due to both the development of more specific toxicants, and of course the cancellation of the DDT registration, and the restrictions on 2,4,5-T use due to environmental protection concerns, the objectives of aerial application of pesticides remain the same. In the case of insecticides the objective remains the suppression of pest outbreaks. The last few decades have witnessed the growth of intensive forestry, and the utilization of a wider variety of timber species (CNA, 1980). This in turn has essentially expanded the number of pest species considered economically important. Those pests now controlled by the widespread use of chemical means are the gypsy moth, the eastern and the western spruce budworm, the douglas-fir tussock moth, and to a limited extent, the mountain, and southern pine beetle. Acreage treated in 1977-1979 with insecticides totaled over 6.5 million acres (CNA, 1980) with the bulk of this being applied aerially.

Herbicide applications may have a variety of program objectives. Most often the objective is release of desired species through the destruction of competing vegetation. The other principal objective of herbicide treatment has historically been site preparation, with less prominent objectives being thinning, insect prevention (as a component of an integrated pest management program), right of way management, and others.

As already noted, the chemicals used, both insecticides and herbicides have changed considerably over the last twenty years. The principle insecticides more recently in use include carbaryl (Sevin) which comprised 84 percent of all aerially applied insecticides between 1975 and 1978 (CNA, 1980), mexacarbamate (Zectran) which was widely used from 1971 to 1974, aminocarb (Matacil), Fenitrothion, and others such as acephate (Orthene), and trichlorfon (Dylox) to a lesser extent. The largest proportion (87 percent) of these have been used in the northeastern U.S. for spruce budworm and gypsy moth control (CNA, 1980). Other insecticides including azinphosmethyl, malathion, dimethoate and carbofuran have been used extensively relative to seed orchards and nurseries in the Southeast (CNA, 1980).

The use of aerially applied herbicides was reduced for some purposes with the banning of 2,4,5-T use in 1980. During the period immediately prior to 1980 1.2 million acres were sprayed annually, with reasonable potential for an additional 2.9 million acres (Row et, 1981). Most of this was conducted on non Forest Service owned land, with only 182,000 acres receiving treatment within the National Forests in 1979 (GAO, 1981).

Both insecticides and herbicides are applied using both fixed and rotary wing aircraft. The bulk of aerial spraying in the West is done using helicopters where the need exists to maximize effectiveness in rough terrain areas. In the East the massive spray requirements led to the use of large aircraft capable of swath width applications of up to 3,000 feet (Irland, 1978).

It is clear that the use of both insecticides and herbicides in the U.S. on forested lands is quite extensive, and must occur over a wide variety of settings. The continued development of intensive forestry practices will place even greater demands upon the effective use of these chemicals. It has been estimated that the loss of 2,4,5-T alone will result in reductions of close to $1 billion in U.S. Forest land (present net worth) in ten years (Row, et al., 1981). Effective spray program planning is absolutely necessary to complement this increasing dependence upon aerially applied pesticides. While it is not possible to accurately predict cost reductions to be realized by such planning, at this early stage, values of 10 percent of gross expenditures would not appear unreasonable.

B. The Role of Aerial Spray Planning and Analysis

Suppression of forest pests and undesirable plant species is an important activity in forest pest management. Planning and analysis, in turn, are important activities in suppression management. This is discussed in depth in Appendix A, which identifies and describes five principal activities in suppression management:

(1) Policy Formulation and Update
(2) Routine Planning and Forecasting
(3) Execution,
(4) Evaluation, and
(5) Research.

The first two of these activities, which constitute the bulk of aerial spray planning and analysis, are discussed briefly below.

Policy formulation and update refers to such policies as pesticide selection, application rate specifications, buffer zone specifications, pest population densities justifying treatment, and meteorological thresholds for cessation of spraying. These policies tend to stand unchanged for several years, during which they may not undergo serious review. Selecting such a policy is tantamount to making a corresponding decision on each spray operation for several years, so the real cost of a poor policy can be high in terms of lost efficiency or adverse impacts.

Routine planning and forecasting refers to the more immediate decisions for a given season. Perhaps the most important of these decisions are the selection, definition, and scheduling of the treatment blocks. Another decision made annually by project is the selection of a spray contractor.

The responsibility for actually setting these policies and making these decisions belongs to a particular state forestry division, or National Forest supervisor, or in some cases,

another state or federal office. Such decision-making normally involves substantial consultation and coordination with higher authorities or outside agencies. The cognizant state forest pest manager might consult with USFS/FPM for spray planning and technical advice. He probably will petition USFS/ S&PF for joint funding, and coordinate accordingly. He must prepare an environmental impact statement which will be reviewed by EPA and state environmental protection authorities. Such consultation and coordination tends to be amicable and cooperative, but in the end the state pest manager must accept EPA's decisions or face the possibility of legal action*, and he must bow to S&PF's demands and constraints or face loss of joint funding. The federal pest manager, similarly, must consider other's positions. So the pest manager must be responsible not only for planning or decision-making, but he must also undertake publicity and persuasive technical argument in order to achieve the program objectives.

The Traditional Approach to Aerial Spray Planning and Analysis

The traditional approach to aerial spray planning and analysis can be characterized as the application of expert judgment by pest managers, field personnel, applicators, pesticide manufacturers, and consulting scientists, supported by research and operational experience. Much of this knowledge, and the operational and experimental results upon which it is based, is communicated through professional journals, reports, and meetings.

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* There is some disagreement over to what extent EPA's approval must be sought for spray program plans. For example, EPA has published an advisory opinion regarding the spruce budworm spray program in the state of Maine specifying buffer zones to be maintained around sensitive areas. A controversy ensued, and EPA has not issued any similar opinions since that time. EPA's input has been primarily at the registration stage for a given chemical use. However, EPA does have the legal right to review EIS's and to consider further restrictions.

Due to funding limitations, much of the supporting operational research is of a trial and error nature flawed with inadequate measurement of variables, small experimental blocks, and reliance on retrospective analysis. Nevertheless, progress has resulted.

Understanding and innovation would undoubtedly grow more rapidly if more spray operations were used as true research experiments employing better defined scientific methods and adequate sampling and measurement, but this adds costs to each phase of an operation (pest population and forest stand survey; operation planning and monitoring; biological sampling, meteorological measurement; pesticide dosage, deposition and drift measurement; pest mortality measurement; overall operation evaluation and documentation). Such increased costs are difficult to justify under austere forest management budgets. However, over the past decade some movement has been made in the direction of more scientific evaluation of aerial spray operations, particularly during the USDA/USFS accelerated program against the tussock moth, the spruce budworm, and the gypsy moth. The USFS Methods Application Group in Davis, California and the Missoula Equipment Development Center have been responsible for technical support to these programs, and also have been working to develop improved understanding of aerial spray science. The Pacific Southwest Forest and Range Experiment Station (Berkeley) have also directed research towards understanding the mortality/dose relationships. If such initiatives can be continued, significant improvement in pest management efficiencies and capabilities can be expected in the future.

An Idealized Approach to Aerial Spray Planning and Analysis

Figure II-1 suggests an idealized approach to aerial spray planning and analysis. This approach is built upon a system of objective, quantitative, validated models used to predict immediate and future spray operation costs, benefits, and environmental

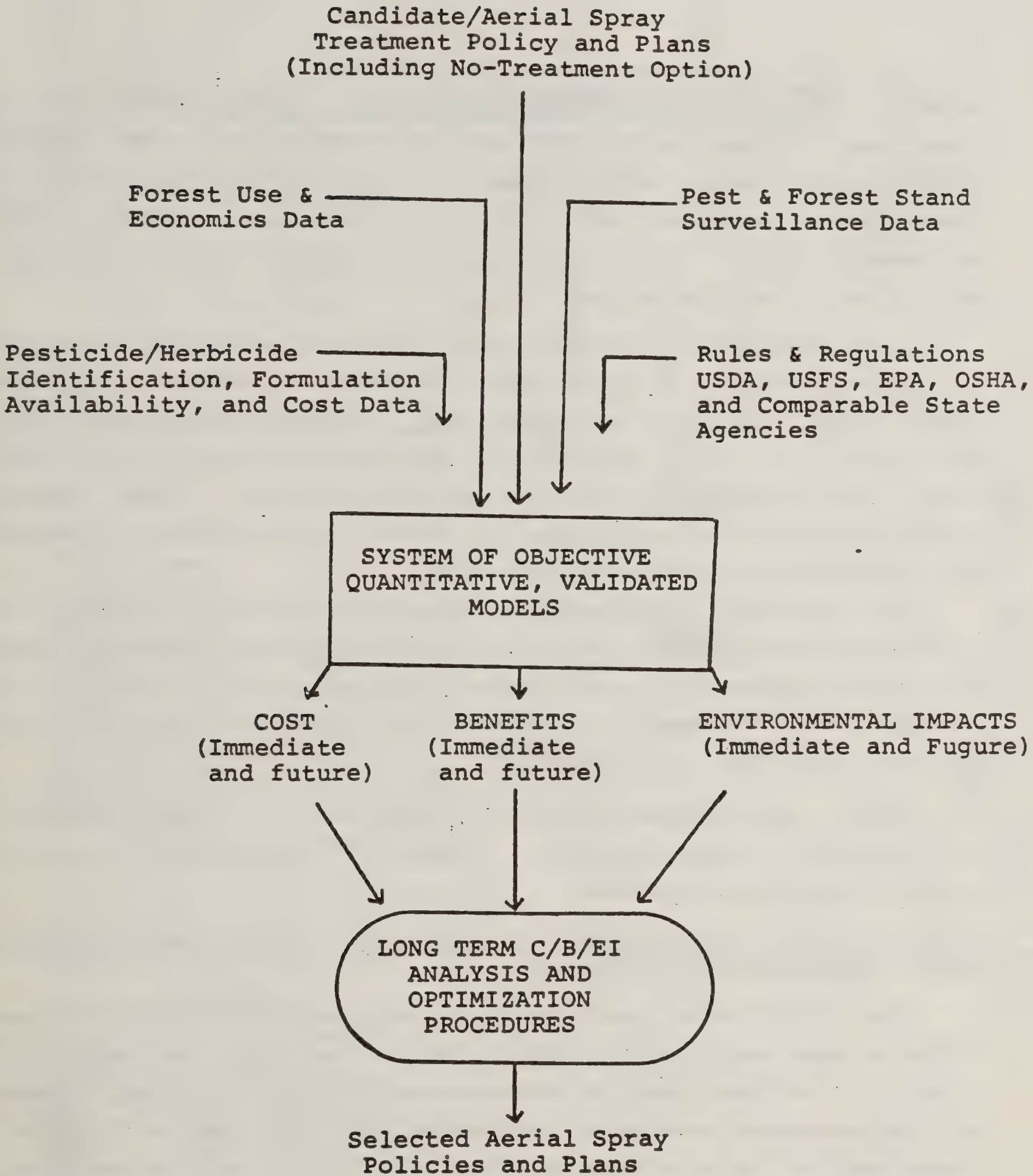


FIGURE II-1

AN IDEALIZED APPROACH TO AERIAL SPRAY PLANNING AND ANALYSIS

impacts under various treatment policies. These models may be nomograms, tables, hand calculator algorithms, or more complex computer programs or subroutines. The system of models makes it possible to determine best policy, approach and plans through systematic C/B/EI (Cost/Benefit/Environmental Impact) analysis and optimization procedures.

A more detailed indication of the required models is shown in Figure II-2. The aerial spray deposition, dosage, and drift model drives the pest (or undesirable species) mortality model. That model, in turn, defines the starting situation for forest stand response/pest population dynamics models. These latter models provide the information on forest stand condition needed to drive forest use economics models.

In addition a range/forest management model is needed to interlink these models in order to interactively estimate costs and effectiveness of future forest management activities and to estimate the economic value of the immediate aerial spray alternatives under consideration.

Also required are models for tabulating mission costs and environmental impact indices. These are envisioned as fairly simple accounting routines.

Contrasting the Traditional and Idealized Approaches to Aerial Spray Planning and Analysis

The traditional and idealized approaches to aerial spray planning and analysis are more similar than is first apparent. Appendix A argues that professional experience - the key element of the traditonal approach - is embodied in subjective but semi-quantitative "models" residing in the minds of the cognizant foresters and forest pest managers. Thus, in traditional aerial spray planning and analysis the pest manager implicitly exercises his models of aerial spray dispersion and deposition, his models of pest mortality, his models of population growth and forest

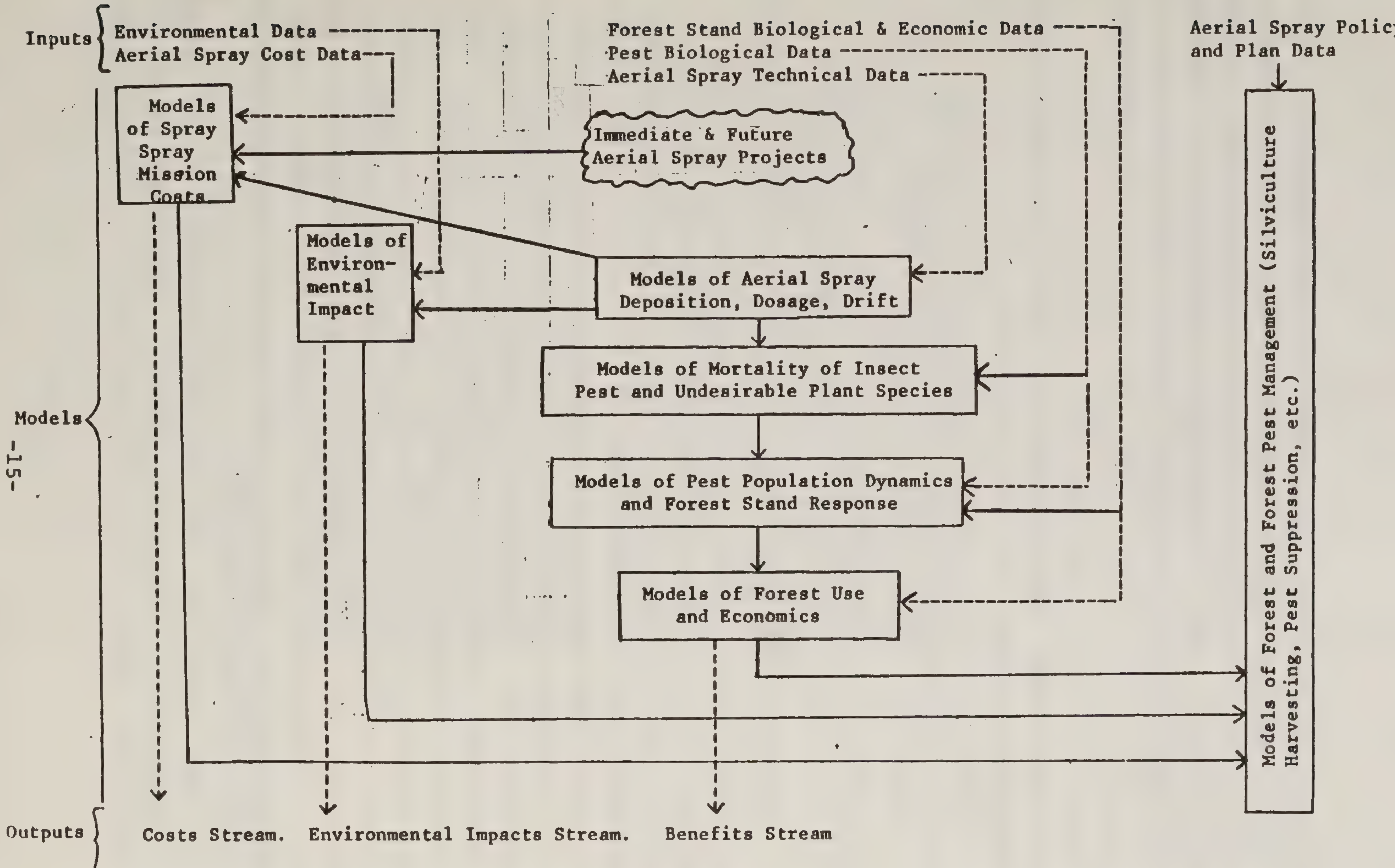


FIGURE II-2

BASIC MODELS SUPPORTING THE IDEALIZED
APPROACH TO AERIAL SPRAY PLANNING AND ANALYSIS

stand response, and <u>his</u> models of forest economics. He uses these subjective models to conduct a subjective, yet implicitly quantitative, evaluation of competing aerial spray treatment policies and plans. So the difference between the traditional and idealized approach appears to be the difference between the subjective and objective models used in the respective approaches.

What then, are the advantages of the idealized approach? There are several:

(1) Scientifically developed and validated models should eventually, and may currently, outperform expert judgment.

(2) This performance advantage is particularly likely and important for the inexperienced forest pest management staff member whose subjective approaches (models) are "immature". Under the idealized system, then, the number of "experts" available for predicting aerial spray consequences should no longer be a scarce commodity. Near real-time adjustments can be made more often, then, since the "expert" will no longer be unavailable.

(3) Quantitative, objective models are far more easily communicated and understood than are verbal, subjective formulations or experience. Objective models can be more clearly debated on their merits. A significant acceleration in the development of forest and pest management science might well result.

(4) Quantitative, objective models make possible more efficient documentation of spray programs and more objective environmental impact statements.

<u>Combining the Traditional and Idealized Approaches to Aerial Spray Planning and Analysis</u>

The traditional and idealized approaches are not completely incompatible. One approach employs a system of subjective experiential "models" while the other employs a system of objective

ones. There is nothing to prevent development and application of a hybrid system consisting of both kinds of models. Objective models can be employed where the requisite scientific understanding is sufficiently good to support them. Expert judgment can be used where necessary, and where circumstances dictate their use.

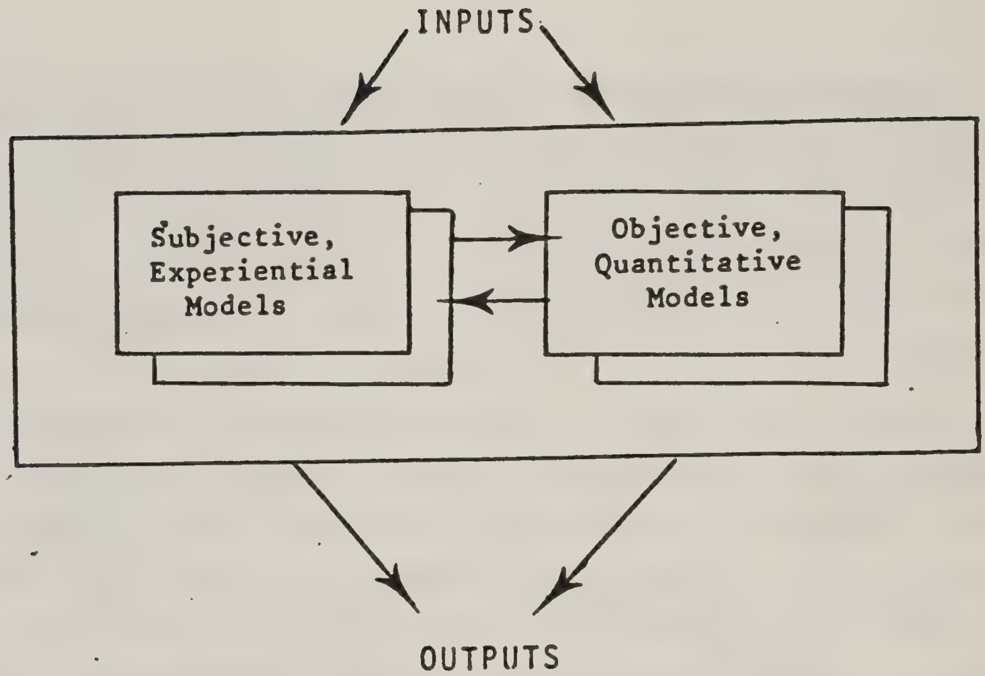
Further - and this is very important - objective, quantitative models can be used to provide forest and pest management personnel surrogate experience, enabling them to form or perfect their subjective models. Although not generally recognized, as such, this has probably been the main function of models developed to date, communicated through studies and reports.

Summarizing, two hybrid approaches to aerial spray planning and analysis can be envisioned, as suggested in Figure II-3.

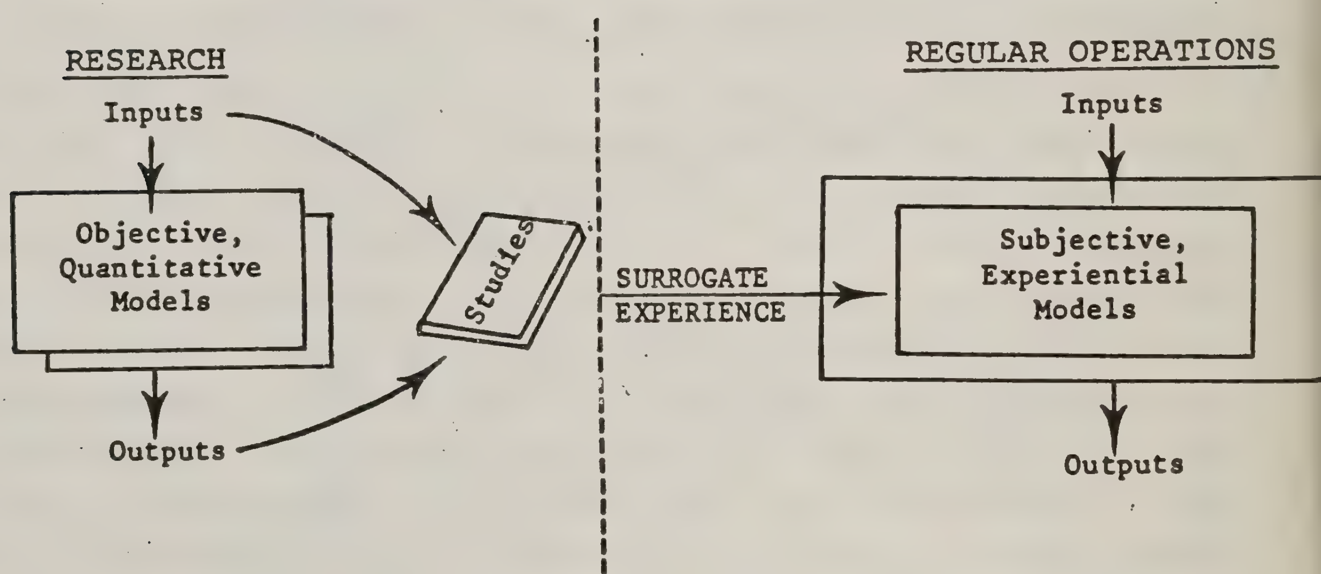
<u>General Status of Quantitative, Objective Model Development</u>

Over the years there have been a significant number of efforts aimed at modeling particular elements of the total pest management process - a pest population model here, a forest economics model there, and pest mortality data compilations everywhere. But for the most part there appears not to have been mounted the sustained, focused effort needed to achieve in-depth understanding and established, employed models. One exception to this is in the area of aerial spray dispersion, deposition, and drift, where work has been continuously sponsored by the U.S. Forest Service, Forest Pest Management Methods Application Group, and the Missoula Equipment Development Center for well over five years, with earlier cooperative support by the U.S. Army, Dugway Proving Ground The results have been encouraging and have provided considerable insight into understanding spray behavior.

Pest mortality and population growth models appear scattered, at best. Mortality and recovery of undesirable plant species is better understood, but quantitative models are not widely available.



CONCEPT: A Hybrid System of Objective and Subjective Models Used During Planning and Analysis



CONCEPT: Objective, Quantitative Models Used To Train Forest and Pest Management Staff, i.e. to Sharpen Their Subjective, Experiential "Models"

FIGURE II-3

TWO CONCEPTIONS FOR HYBRID APPROACHES TO AERIAL SPRAY PLANNING AND ANALYSIS

Forest economic models are available as are simple mission cost and environmental impact models. In the next section the status of models will be discussed in more detail.

SECTION III

A DISCUSSION TOWARDS IDEALIZED AERIAL SPRAY PLANNING AND ANALYSIS

GENERAL

In the last section the concept of idealized aerial spray planning and analysis was introduced and compared to the system currently in place. In this section the benefits to be realized at stages in moving toward an idealized system are explored.

It is not possible to confidently prescribe the absolutely best course for ASPAS (Aerial Spray Planning and Analysis System) evolution - the uncertainties in model research and development effort, economic and environmental payoffs, and future developments in aerial spray technology are far too great. But it is possible to suggest priorities based on reports by, and discussions with, cognizant field personnel, researchers and managers, and, thus, to fashion suggestive ASPAS stages or "mods" incorporating selective improvements. It is even possible to suggest or speculate on the economic present value of achieving certain degrees of ASPAS improvement and from this to suggest current investments justified to achieve such improvement.

The discussion in this section is still fairly general. In a later section we will recommend specific enhancements to current ASPAS software, and estimate corresponding manpower requirements.

PRIORITIES FOR ASPAS MODEL IMPROVEMENT

For this analysis we recognize three broad classifications of model improvement: (1) increased model scope, (2) improved model validity (faithfulness, accuracy), and (3) ease of use. Each is important. The most accurate system of models in the

world will have little overall impact if it is restricted to one type of aircraft, a narrow band of weather conditions, one type of foliage, one pest, one pesticide, and droplets in a certain range only. On the other hand, a system of models that can be applied to most aerial spray operations, but gives no more accuracy than field judgment, effects no real economies. Finally, in order to be useful, a system of models must be used - it will not be if input set-up and output interpretation are too tedious. The suggestive ASPAS mods presented below will encompass some of each type of improvement.

What specific areas of modeling should receive the most attention? To address this question, first consider Table III-1, adapted from A Problem Analysis - Forest and Range Aerial Pesticide Application Technology. A group of Forest Service specialists developed the problem area prioritization shown, and indicated to what degree successful problem resolution would contribute to drift reduction, cost reduction, and increased efficacy. As our bracketed notes indicate, however, many of these problem areas require technological - not analytic - fixes. Also note that "Cost Reduction" apparently refers to immediate cost reduction (current spray project) and not to long term cost reduction (realized through obviated retreatment or salvage). In actuality increased project efficacy effects economies both in such long term cost reduction and in long term benefit generation (e.g. increased harvest yields). Further, reducing the need for retreatment obviously reduces long term environmental impact. Based on such consideration we propose the ASPAS modeling area prioritization presented in Table III-2. This will be reflected in the ASPAS mods suggested Section III.

POSSIBLE ASPAS EVOLUTIONARY MODIFICATIONS

The tables in Appendix D indicate potential attributes and capabilities of the constituent ASPAS models. Under each category the attributes generally are limited in the order they

TABLE III-1

A CONSENSUS ON PROBLEM AREA PRIORITIZATION

PROBLEM AREA	PRIORITY 1/	EXPECTED CONTRIBUTION TO			[TYPE OF ISSUE] 2/
		DRIFT REDUCTION	[MISSION] 2/ COST REDUCTION	INCREASED EFFICACY	
Aircraft Delivery Systems	9	High	High	High	[Technology issue.]
Technology Transfer	9	High	High	High	[Technology issue.]
Spray Behavior	8	High	Medium	High	[Modeling issue.]
Aircraft Guidance	7	High	Low	High 3/	[Technology issue.]
Application Strategy	6	Medium	Low	High 3/	[Modeling issue.]
Meteorology	6	High	Low	Medium	[Modeling issue.]
Spray Drift	5	High	Low	Low	[Modeling issue.]
Biological Interface	4	Low	Low	High 3/	[Modeling issue.]
Sampling	3	Low	Low	Low	[Technology issue.]
Pesticide Safety	3	Low	Low	Low	[Technology and procedures issue.]

Adapted from Ekblad et al., 1979

1/ Priority on scale from 1 (lowest) to 10 (highest).

2/ Our comments and additions above are in brackets.

3/ [NB! High efficacy is generally translated into long term reductions in costs and environmental impacts since future retreatment is reduced.]

TABLE III-2

MODELING PRIORITIZATION BASED ON LONG-TERM REDUCTIONS IN ENVIRONMENTAL IMPACT, PEST MANAGEMENT COSTS, AND FOREST VALUE LOST

MODELING AREA	LONG TERM ENVIRONMENTAL IMPACT REDUCTION	LONG-TERM PEST MANAGEMENT COST AND FOREST VALUE LOSS REDUCTION
Spray Behavior	Very High	High
Application Strategy	High	Medium
Biological Interface	Medium High	Medium High
Meteorology	High	Medium
Spray Drift	High	Low

Adapted from Ekblad et al., 1979

would be expected to be achieved as ASPAS evolves. Therefore it is possible to represent a given evolutionary stage or "mod" by indicating the line of demarcation between achieved and yet-to-be achieved attributes. In this way one possible progression of ASPAS mods, is indicated in Appendix D (by horizontal lines with corresponding mod numbers at the right). This sample progression proceeds as follows:

- Starting with Mod 0 (current system), in which the only objective models employed are those addressing aerial spray dispersion, deposition and drift, those addressing spray mission costs (the procedure developed by MEDC), and those addressing environmental impact.
- Mod 1 represents (1) improved aerial spray dispersion, deposition and drift models, expanded to address sloped terrain, and somewhat simplified in terms of input preparation and output presentation; (2) objective preliminary pest mortality models, (3) implementation of an interactive mode to increase user convenience, and (4) implementation of the mission cost and environmental impact accounting models on the USFS Ft. Collins computer.
- The Mod 2 entails (1) improvements in the aerial spray deposition, and drift models, including modification to improve validity, and an expansion in scope to better address deciduous forests, (2) improvements in the pest mortality models, including modification to improve validity and increase user convenience; and (3) implementation of interactive versions of the mission cost and environmental impact accounting models to improve user convenience.
- Mod 3 involves (1) further upgrading of the aerial spray dispersion, deposition and drift models, plus implementation of hand calculator emulation for field use; and (3) enhancement of the mortality models, to include more useful measures of mortality.

Further Mods would involve further incremental enhancements in the APSAS models. At Mod 5 it is suggested that objective models

of pest population dynamics and forest response be introduced, as well as objective models of forest and forest pest management.

Objective models of forest use and economics, although available to some degree now, might not be introduced until Mod 10, at which time the scope and validity of the other models might be adequate to support them with meaningful data.

In each of these suggestive ASPAS Mods, those elements not treated objectively would be handled judgmentally by cognizant forest and forest pest managers, assisted by the information provided by the objective models.

It can readily be seen that a large number of possibilities exist for specification of the sequence of development of the ASPAS system. Section IV a set of criteria for choosing among the possibilities is presented, and specific recommendations for the sequence of development are made.

SUGGESTED ECONOMIC EVALUATION OF ASPAS EVOLUTION

Overview

The future value of an Aerial Spray Planning and Analysis System will depend on four factors: (1) how much it is used, (2) to what degree it improves the efficiency with which spraying is accomplished, (3) the benefits of treatment where successfully undertaken, and (4) such indirect benefits as the focussing of research, reduction of environmental impacts, or the education of forest workers and aerial applicators. Although it is not possible to predict such future factors with confidence, it is useful to speculate on optimistic and pessimistic bounds, at least for the first three factors. The fourth factor, indirect benefits, defies meaningful quantitative speculations, but is definitely not unimportant.

In this analysis we will refer to ASPAS usage in terms of treatment budget, e.g. ASPAS usage on $200,000 worth of aerial spray projects; this $200,000 will provide aerial spraying on an acreage dependent on spray program efficiency.

ASPAS efficiency will be defined in terms of increased acreage effectively treated for a given budget:

$$E_m = \text{(Efficiency) Mod m} = \frac{\left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Mod m}} - \left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Now}}}{\left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Now}}}$$

Even if ASPAS does not directly reduce the cost of spraying a given acre, but rather improves the quality of the treatment, this can often be thought of in terms of increased acreage treated in one of two ways: (1) the improved treatment may give rise to a higher economic yield (e.g. stumpage dollars) which can be thought to be used to produce increased acreage treatment; (2) the improved treatment may obviate a future treatment of the same acreage, and this may be considered as added acreage treated (with appropriate discounting). ASPAS use would also result in greater environmental safety which is not easily quantifiable, except in cases where acreage could be treated safely which could not have been treated without ASPAS.

The final factor used in this economic analysis is the current benefit to cost ratio on treated acreage. Typically in agriculture and forestry applications, this ratio tends to be high (10:1 or greater) for all acreage treated, even the lowest priority blocks, since budgets do not generally permit treatment of all qualifiying areas.

The above factors will be combined to give an estimate of benefits from a given ASPAS system, MOD m, in a future year. Let C be the budget for aerial spray projects in which ASPAS is used. Let E be the efficiency for the given ASPAS system. Let R be the present benefit/cost ratio for treatment; generally this should

be the marginal rate (i.e. for the lowest priority acreage) rather than the average rate. Then the ASPAS-induced economic benefit will be for a given future year*

$$DB = R \cdot E \cdot C$$

This benefit will then be expressed as a present benefit by employing standard economic discounting using a 10 percent discount rate. The present value of the Mod in ASPAS system in year n is then:

$$PV = \frac{DB}{(1 + 0.10)^n}.$$

---

* Justification:

$$DB = (\text{Benefits})_{\text{new}} - (\text{Benefits})_{\text{old}}$$

$$= \left(\frac{\text{Benefit}}{\text{Acre}}\right)\left(\frac{\text{Acreage}}{\text{Treated}}\right)_{\text{Mod m}} - \left(\frac{\text{Benefit}}{\text{Acre}}\right)\left(\frac{\text{Acreage}}{\text{Treated}}\right)_{\text{Now}}$$

$$= \left(\frac{\text{Benefit}}{\text{Acre}}\right)\left[\left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Mod m}}\left(\frac{\text{Program}}{\text{Cost}}\right) - \left(\frac{\text{Acreage}}{\text{Dollar}}\right)\left(\frac{\text{Program}}{\text{Cost}}\right)\right]$$

$$= \left(\frac{\text{Benefit}}{\text{Acre}}\right)\left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Now}}\left[\frac{\left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Mod m}} - \left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Now}}}{\left(\frac{\text{Acreage}}{\text{Dollar}}\right)_{\text{Now}}}\right]\left(\text{Program Cost}\right)$$

$$= \left(\frac{\text{Benefit}}{\text{Dollar}}\right)_{\text{Now}}\left(\begin{array}{c}\text{Efficiency of}\\ \text{ASPAS MOD M}\end{array}\right)\left(\frac{\text{Program}}{\text{Cost}}\right) = R \cdot E \cdot C$$

The total present value of future benefits is then found by summing over all future years.

In order to address the advisability of ASPAS development we then suggest optimistic and pessimistic projections for ASPAS program development costs. Then we will discount these costs in the same way as the projected benefits in order to obtain a present cost projection.

The ratio of present benefits to present costs serves as an index on the utility of ASPAS development.

Suggestive Economic Benefits of ASPAS Evolution

Tables III-3 and III-4 display the assumed and derived economic measures of a 10-mod ASPAS evolution program under moderately optimistic and pessimistic projections, respectively. Under both projections we have assumed a 20 year total development effort. It is assumed that the equivalent benefit/cost ratio for treatment of added acreage is 10:1 optimistically, and 1:1, pessimistically.

Efficiency is assumed to grow to 80 percent or 40 percent under the optimistic and pessimistic projections. This corresponds to achieving the same degree of pest control with 56 cents and 71 cents, respectively, that is now achieved with every dollar. How could equivalent pest control be achieved with 56¢ on the dollar? This might come short, say, by reducing the amount of pesticide required (by optimizing droplet spectrum), by increasing the "spraying day" (by determining suitable flight and spray parameters for meteorological conditions now prohibitive), and by better selecting blocks for treatment (avoiding treatment of insect population about to collapse anyway, say), and by achieving a greater rate of success on treated acreage.

The size of the treatment program in which ASPAS is employed is assumed to grow optimistically to \$15 million or pessimistically to \$2.5 million in 20 years. To put these figures in perspective, spruce budworm aerial spray pest control programs have

TABLE III- 3

SUGGESTIVE ASPAS EVOLUTION BENEFITS
UNDER MODERATELY OPTIMISTIC ASSUMPTIONS

ASPAS MOD	YEARS APPLIED	R = MARGINAL B/C RATIO	E = ASPAS EFFICIENCY	C = ASPAS-PLANNED TREATMENT BUDGET (1981 DOLLARS)	ANNUAL ASPAS BENEFITS (1981-DOLLARS)
0	1982	10	12%	$40K	$50K
1	1983	10	14	$ 70K	100K
2	1984-1985	10	18	$220K	$400K
3	1986-1987	10	24	$830K	$2,000K
4	1988-1989	10	31	$3,200K	$10,000K
5	1990-1991	10	50	$4,000K	$20,000K
6	1992-1993	10	60	$6, 700K	$40,000K
7	1994-1995	10	70	$8,600K	$60,000K
8	1996-1997	10	74	$10,800K	$80,000K
9	1998-2000	10	76	$13,200K	$100,000K
10	2001 on	10	80	$15,000K	$120,000K

Total Present Value of ASPAS Benefits = $360 million (using 10 percent discount rate)

TABLE III-4

SUGGESTIVE ASPAS EVOLUTION BENEFITS
UNDER MODERATELY PESSIMISTIC ASSUMPTIONS

ASPAS MOD	YEARS APPLIED	R = MARGINAL B/C RATIO	E = ASPAS EFFICIENCY	C = ASPAS-PLANNED TREATMENT BUDGET (1981 DOLLARS)	ANNUAL ASPAS BENEFITS (1981-DOLLARS)
0	1982	1	12%	$40K	$5K
1	1983	1	12%	$60K	$7K
2	1984-1985	1	12%	$80K	$10K
3	1986-1987	1	13%	$150K	$20K
4	1988-1989	1	15%	$340K	$50K
5	1990-1991	1	25%	$800K	$200K
6	1992-1993	1	30%	$1,300K	$400K
7	1994-1995	1	35%	$1,700K	$600K
8	1996-1997	1	37%	$2,100K	$800K
9	1998-2000	1	38%	$2,300K	$900K
10	2001 on	1	40%	$2,500K	$1,000K

Total Present Value of ASPAS Benefits = $3 million (using 10 percent discount rate)

averaged over $4 million per year over the past ten years. Forest site preparation and release applications with herbicides are expected to involve well over 1 million acres per year at costs of some $40/acre. So there is easily $50 million/year of aerial spray operation in forest and forest pest management. Under pessimistic and even under the optimistic assumptions the bulk of this spraying would be conducted without ASPAS involvement.

Suggestive Costs of ASPAS Evolution

To appreciate the advisability of ASPAS evolution we need present costs as well as benefits. Under optimistic conditions we would expect that ASPAS development would require about $100K per year for 20 years. Under pessimistic conditions it would require $500K per year. To put these figures in perspective, development of the FSCBG model has required on the order of $100K/year for the past seven years. It should be emphasized that the entire cost of ASPAS evolution is not expected to be borne by the Forest Service, since the project will be aided by independent modeling efforts of extra USFS agencies. The U.S. Army, for instance, has developed chemical dispersion models over the years and is in the process of initiating a major model upgrade and enhancement program. Modeling areas currently receiving funding by the army include methods of predicting cloud travel in forest as well as urban terrain (personal communications with Mather Hutton, U.S. Army Chemical Systems Laboratory, Edgewood, Maryland, and Ron Cionco, Atmospheric Sciences Laboratory, White Sands), and measurement of droplet size distribution of insecticide and herbicide sprays (Michael Travis, Fort Detrick, Maryland). The army is willing to make the resultant models and research available to the USFS, and pursue cooperative development.

Canadian workers, expecially in New Brunswick, have also been active in developing aerial forest spray models (e.g. see

Picot and Kristmanson, 1980; Picot et al., 1980; and Tennankore et al., 1980). The Canadians are likely to continue their efforts, focussing on the spruce budworm, and they have expressed an interest in cooperation.

The Animal and Plant Health Inspection Service USDA (AHPIS) is also currently funding an aerial spray modeling project aimed at producing a modeling system which is easily field-deployable (Project officer: John Wood, APHIS-PPQ, Hyattsville, Maryland). The APHIS modeling effort shares many requirements with modeling appropriate for Forest Service purposes.

Cooperation and coordination between the USDA - Forest Service and other agencies interested in aerial spray modeling should be developed to the maximum extent possible in order to prevent duplication and in order to obtain information and develop methods to an extent which would not be possible if all of these agencies work on their own. A careful mix of cooperation and competition could accelerate ASPAS evolution and significantly reduce Forest Service costs.

The Bottom Line

The present value of the optimistic and pessimistic ASPAS development cost streams are $850 thousand and $3.4 million, respectively. The present value of ASPAS benefits is optimistically $360 million and pessimistically $3 million. So under our optimistic assumptions ASPAS evolution would show a very favorable 420:1 benefit/cost ratio. Under the pessimistic assumption ASPAS development would not be justified considering the 0.9:1 benefit/cost ratio, but would not be terribly inefficient. On the whole, we feel these figures support ASPAS development.

This analysis has been necessarily speculative, and we invite the reader to argue the assumed cost and benefit streams and substitute his own. Table III-5 displays in detail the present value calculations and indicates how they can be revised.

TABLE III-5

DETAILS OF CALCULATIONS FOR SUGGESTIVE ASPAS BENEFITS AND COSTS

		OPTIMISTIC		PESIMISTIC	
Mod	Year(1) Applies	Annual Benefits ($1000)	Present Value (10% Discount Rate)	Annual Benefits ($1000)	Present Value (10% Discount Rate)
0	1	50	$50[(1.1)^{-1}] = 45$	5 [ ] =	4.5
1	2	100	$100\,[(1.1)^{-2}] = 83$	7 [ ] =	5.8
2	3,4	400	$400[(1.1)^{-3}+(1.1)^{-4}] = 574$	10 [ ] =	14.3
3	5,6	2000	$2000[(1.1)^{-5}+(1.1)^{-6}] = 2371$	20 [ ] =	23.7
4	7,8	10000	$10000[(1.1)^{-7}+(1.1)^{-8}] = 9797$	50 [ ] =	49.0
5	9,10	20000	$20000[(1.1)^{-9}+(1.1)^{-10}] = 16193$	200 [ ] =	161.9
6	11,12	40000	$40000[(1.1)^{-11}+(1.1)^{-12}] = 26765$	400 [ ] =	267.6
7	13,14	60000	$60000[(1.1)^{-13}+(1.1)^{-14}] = 33180$	600 [ ] =	331.8
8	15,16	80000	$80000[(1.1)^{-15}+(1.1)^{-16}] = 36562$	800 [ ] =	365.6
9	17,18,19	100000	$100000[(1.1)^{-17}+(1.1)^{-18}+(1.1)^{-19}] = 54121$	900 [ ] =	487.1
10	20,21,...	120000	$120000[(1.1)^{-20}/0.1] = 179372$	1000 [ ] =	1486.4

Total Present Value = 35,806
= $360M

Total Present Value = 3197.7
= $3M

SUGGESTIVE PRESENT COST OF ASPAS EVOLUTION

OPTIMISTIC

$100K/YR FOR 20 YEARS

$$
\begin{aligned}
PC &= \$100K\ [(1.1)^{-1}+(1.1)^{-2}+\ldots+(1.1)^{-20}] \\
&= \$100K\ [(1.1)^{-1}+(1.1)^{-2}+\ldots] \\
&- \$100K\ [(1.1)^{-20}[(1.1)^{-1}+(1.1)^{-2}+\ldots] \\
&= \$100K \left\{ \left[\frac{(1.1)^{-1}}{1-(1.1)^{-1}}\right] - (1.1)^{-20} \left[\frac{(1.1)^{-1}}{1-(1.1)^{-1}}\right] \right\} \\
&= \$100K\ \left[\frac{1}{.1}\right] - (1.1)^{-20} \left[\frac{1}{.1}\right] \\
&- \$100K\ [8\ 514] = \$850
\end{aligned}
$$

PESSIMISTIC

$400K/YR FOR 20 YEARS

PC = $400K [8.514] = $3400K

One final observation should be made. The largest contributions to the present value of the ASPAS benefit streams come from the farther future, while the largest contribution to the present value of the ASPAS costs come in the near future. ASPAS development therefore represents a far-sighted investment in future forest management.

SECTION IV

RECOMMMENDED AERIAL SPRAY PLANNING AND ANALYSIS SYSTEM EVOLUTION

A. System Development Pathways

Many possible improvements to the FSCBG model for aerial spray analysis have been identified in the course of the study. These improvements include some structuring of the input data, program control, the underlying mathematical models themselves, the nature and format of output data, and the data base necessary to support applications of the models. Development of a generally useful Aerial Spray Planning and Analysis System will require not only improvement of the existing tools, but also their extension and the development of new modules to represent situations and aspects not previously included, notably the biological interface.

The specific enhancements which have been considered vary widely in their value to the overall system, as well in as the cost, manpower, and time which would be required for their development. The enhancements are also interdependent in terms of their value, cost, and feasibility. Consequently, these enhancements cannot be considered independently, but must be related to overall objectives. The individual tasks involved must be evaluated and prioritized on the basis of a general plan for system development.

The formulation of such a plan was undertaken with the following objectives:

- To develop a system which would be very useful operationally in a short time, and whose usefulness could be expanded by subsequent development. The plan

would be designed to produce discrete generations of the system as a result of correlated development of component parts producing progressively more useful versions.

- Initial phases of the development should concentrate on those enhancements for which the greatest payoff is expected, which can be completed at an early date and without undue cost. The plan should be driven by the need to produce adequate estimates of biological effects.

- Modularity should be maintained throughout the system development to allow ease of modification of the components and replacement of modules when better or more efficient ones become available or if a new sub-model is required by a new situation. Modules should also be able to be bypassed if they are not needed.

- The plan should aim to produce a system which is applicable to the range of situations which represent the most likely uses, including major insect control and herbicide application operations, on all common forest types.

- Usability of the system in terms of ease of data input, program control, and handling and interpretation of output data should be emphasized. These factors are expected to be important in determining the extent to which the system will be used.

- The system should be designed to produce information of a kind and format which can easily be transferred to field use. The Aerial Application Technology Workgroup and forest pest managers both within and outside of the Forest Service have identified information transfer as an aspect in need of improvement. This should be considered an important aim even in early stages of project planning.

An evolutionary scheme for the development of an ASPAS system is shown in Figure IV-1. It represents a phased developmental process, designed to meet the objectives listed above.

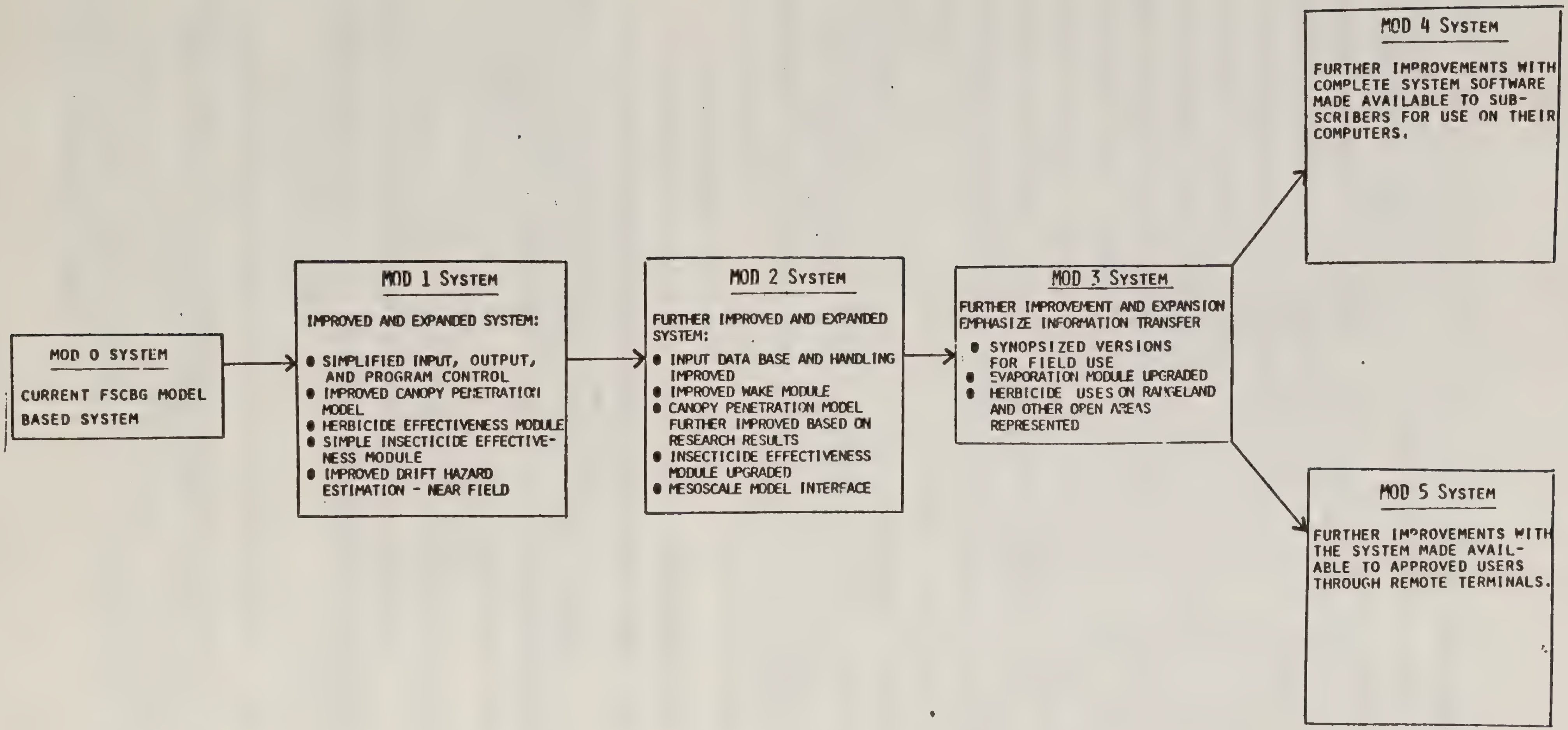


FIGURE IV-1

ASPAS EVOLUTIONARY SCHEME

The individual generations of the system, referred to as MOD 0, MOD 1, etc., are discussed in the following paragraphs. It is recommended that the first three phases of the development be undertaken first, resulting in the MOD 3 ASPAS system. MOD 4 and MOD 5 would then represent possible directions for subsequent development. It should be emphasized that the Forest Service need not (and should not) commit itself to a final design for the system. The continuation and the exact nature of the development should be reviewed at each stage and the options analyzed in the light of the existing circumstances. The continuation of the development process should certainly depend not only on the extent of use of the system but also on the forecasted use over several succeeding years, and its relationship to the cost of the system and the available budget. The development of certain aspects of the system will be contingent upon the satisfactory completion of ancillary research and development tasks. The nature of the final system also should depend on the resolution of accompanying organizational issues, some of which are discussed in the following section.

<u>MOD 0 System</u>

- Model and Software Requirements:

  Current FSCBG Model which includes a simple wake model, a Gaussian above - canopy dispersion model, evaporation models, and the Barry/Grim Model for canopy penetration and deposition.

- Configuration/Organization:

  FSCBG program maintained on the USFS UNIVAC computer in Fort Collins, Colorado. Used by USFS-FPM specialists, Davis, California.

- Documentation:

  FPM internal documentation of high quality.

- Concept of Use:

National focal point - analyses of prospective spray programs are conducted in response to client requests by FPM specialists who produce prescriptions of how blocks are to be sprayed. Minimal personnel needs to maintain this service can currently be met by an aerial application specialist and a system manager familiar with both the models and data processing techniques. Current and prospective clients include U.S. Forest Service, other USDA, the Bureau of Land Management (BLM), the Bureau of Indian Affairs (BIA), state and private pest managers, the Environmental Protection Agency, the U.S. Army, and the U.S. Air Force.

<u>MOD 1 System</u>

- Model and Software Requirements:

Improved and expanded version of the FSCBG model and program, incorporating:

-- interactive program control,

-- simplified and flexible input routines,

-- output summary routines including graphical displays and summarizing statistics,

-- an improved version of the canopy penetration module, primarily based on theoretical considerations,

-- an herbicide effectiveness module,

-- a simple insecticide effectiveness module based on currently available models and data,

-- modification of the simulation and incorporation of an appropriate measure to allow estimation of near-field drift hazard.

- Configuration/Organization:

Program maintained on the USFS UNIVAC computer in Ft. Collins. Used by USFS-FPM specialists, including regional personnel with some familiarization. Accessible by remote terminal over telephone lines.

- Documentation

  FPM internal documentation of high quality.

- Concept of Use:

As for the MOD 0 system, FPM specialists maintain a centralized center, responding to client requests for prescriptions of how blocks are to be sprayed, but also responding to requests for information to support environmental analyses. In these cases, the FPM specialists will supply the results of calculations of expected on-site and near-field exposures which can be used by the clients in analysis of corresponding hazards and risks. Personnel needed to support this system would certainly include an aerial pesticide application specialist and a system manager at a minimum. While these two specialists can probably operate and maintain the system for the near future, demands on their time can be expected to increase as client requests increase. Regional specialists with some training could access the system directly by remote terminals.

<u>MOD 2 System</u>

- Model and Software requirements:

A further expansion and improvement of the models and programs, incorporating:

-- further simplification of input data handling, especially by expanding the supporting data base,

-- incorporation of an improved wake module,

-- further improvements to the canopy penetration module, reflecting the results of supporting research,

-- an improved version of the insecticide effectiveness module, reflecting relevant research,

-- facilitation of long-distance drift hazard analysis by interfacing with an existing mesoscale model. Work on this interface could be done under MOD 1 if the U. S. Army participates.

- Configuration/Organization:

Program maintained on the USFS UNIVAC computer in Ft. Collins by USFS-FPM specialists.

- Documentation:

  -- User documentation of high quality for use by FPM specialists.

  -- Maintenance documentation of high quality for internal FPM use.

- Concept of Use:

Use is primarily centered at a national FPM focal point, where FPM specialists maintain the system and respond to requests for:

  -- prescriptions for how blocks are to be sprayed,

  -- calculations of expected on-site and near-field exposures to support environmental analyses, and

  -- calculations of amount and pattern of pesticide subject to long-distance drift, as input to meso-scale meteorological models of client analysts.

Regional specialists with some training could also access the system directly by remote terminals.

A formal database could also be maintained containing available field data from both deposit monitoring and biological mortality surveys. This database could contain the corresponding model predictions paired with each field observation, from routine field monitoring as well as any validation studies. This database would provide a means for routine feedback to the managers of the system, allowing them to assess the model's accuracy and even to improve upon it.

<u>MOD 3 System</u>

- Model and Software Requirements:

Further improvement and expansion of the system, with facilitation of information transfer as a primary goal:

-- Synopsis versions created for specific field situations, for use on hand-held calculators or microcomputers,

-- Evaporation module improved to reflect research results,

-- A new module to represent pesticide (especially herbicide) use on rangeland and other open areas.

- Configuration/Organization:

-- Primary program maintained on the USFS computer in Fort Collins by USFS-FPM specialists, who develop and distribute synopsis versions tailored to specific uses.

-- Synopsis programs to be used by Forest Service regional pest managers, as well as specialists in state and other client organizations.

- Documentation:

-- Main system user documentation primarily for internal FPM use but also for reference use of client analysts.

-- Main system maintenance documentation for internal FPM use only.

-- Synopsis versions accompanied by user documentation of high quality, but the relevant programmer analyst documentation would be maintained by FPM.

- Concept of Use:

FPM specialists still maintain a national center which can respond to requests for advice on:

-- how blocks should be sprayed.

-- expected on-site and near-field exposures to support environmental analyses, and

-- amount and pattern of pesticide subject to long distance drift, which could be input to mesoscale meteorological models by client analysts.

FPM will also develop and distribute synopsis versions tailored to specific use situations. Applications would include aerial pesticide application parameter prescription, effectiveness prediction, and drift hazard estimation. Particular versions would be restricted in applicability to specific forest types, pests, pesticides, and application modes. These synopses

could be developed to handle the most commonly occurring situations and would allow field personnel with proper documentation to plan routine projects without reference to the main ASPAS system. New or unusual situations and most research applications will require reference to the main system.

FPM personnel in charge of the system would be expected to spend less time on routine consultations. Their time would be needed for monitoring of field use of the synopsis versions and training associated with them. Another specialist with biometry or modeling expertise would be needed to develop synopses of new situations.

MOD 4 System

- Model and Software Requirements:

  Further improvements with complete system software made available to subscribers for use on their own computers.

- Configuration/Organization:

  System maintained by FPM in versions for selected computers.

- Documentation:

  -- High quality documentation for main system users and synopsis version users.
  -- Maintenance documentation for FPM use.
  -- ASPAS System-User Newsletter

- Concept of Use:

  Tapes of the entire system software could be made available to interested subscribers, such as US Forest Service, Bureau of Land Management, state and private pest managers; APHIS, EPA, USDA/AID international forestry programs, universities, or researchers of the agricultural chemicals industry. These users may in turn submit candidate modifications and additions to

the system, based on their experience, to FPM for possible inclusion in ASPAS. They may also submit items for the newsletter on system performance, pest management models, etc.

FPM would maintain the system software and publish the newsletter in addition to the activites already identified under MOD 3. While remote access is possible in MODs 0-4 improvements will be necessary to perimt many users to access the system without continuing supervision.

MOD 5 System

- Model and Software Requirements:

Further improvements with the system made available to approved users through remote terminals. Simultaneous use by more than one user will require software for terminal interfacing and for control of program modules and files.

- Configuration/Organization:

System maintained by FPM on USFS Fort Collins computer for use by approved clients within the U.S. Government, who would access the system by remote terminals via FTS telephone lines. The system could also be made available to other users, including private industry, by allowing the system to be installed by one or more commercial computer service organizations.

- Documentation:

  -- High quality documentation for main system users and synopsis version users.

  -- Maintenance documentation for FPM use.

  -- Machine-based system bulletins.

- Concept of Use:

The system manager provides for FPM and other U.S. Government users to access the system resident on the USFS UNIVAC computer. FPM specialists maintain the system and post system bulletins on a publicly-accessible file, and distribute user manual modifications and revisions as needed. FPM also continues the activities already identified under MOD 3.

The users may submit candidate modifications and additions to the system, based on their experience, to FPM for possible inclusion in ASPAS. They may also submit items for the system bulletins concerning system performance, availability of correlative research reports, etc.

The software for the ASPAS system could be made available to commercial time-sharing services who would provide access to non-government users at no cost to the government. The services could charge their usual rates for use of their computing facilities, but no fee would be paid for use of the software.

B. <u>Organizational Design and System Development Issues</u>.

Forest Pest Management specialists, in the role of supplying technical assistance in planning aerial pesticide application projects, constitute a service organization in that a service is being performed for a set of clients. A strategic-level analysis of a services organization typically focuses on three elements:

- the product (or line of products),
- the clientele (or market), and
- the delivery system.

The essential characteristics of all three of these elements must be coordinated for a services organization to be successful.

The products in this case are generally forms of analysis, information, and advice concerning aerial spray programs. They are based on experience and expert opinion as well as on computer studies. This report and the ASPAS System itself are concerned primarily with the computer-oriented aspects of this product line. However, all three elements (products, market, and delivery system) must be considered in an overall strategy. Strategic level concepts for FPM regarding the ASPAS have been presented under "concept of use" for the MOD 0 through MOD 5 systems in the preceding section. Other strategic level points could also be considered, some of which are beyond the scope of this report. All of these strategic concepts should be evaluated as they relate to the market, products, and delivery system.

The market element in the present system is generally made up of forest pest management planners. They include U.S. Forest Service personnel operating on National Forest System lands, as well as state and private forestry cooperators.

The delivery system is highly variable, with possibilities under the current system ranging from published reference material and guides made freely available, to supplying a specialist who can give advice based on experience, expert

opinion, and computer calculations, to supplying tables which summarize important aspects of computer model runs for a specific situation.

The value of potential products depends on the extent of the market they reach. The pertinent market must be identified and evaluated by an appropriate measure of activity. The aerial spray planning market for which the ASPAS is to be aimed could be measured by: .

- The number and extent of spray programs to be planned,
- The level of decision making spending involved, and
- The level of effect obtained by the decisions.

The first two of these are the most readily identified and most usually considered aspects. The third, the level of effect, is not easily quantified and usually considered only subjectively (often implicitly) in methods evaluation and development work. It can, however, be of overriding importance. For example, when faced with the prospect of losing the use of the herbicide 2,4,5-T, the forest research community published many reports on the costs of alternative methods of vegetation control. However, a panel of U.S. Forest Service experts (Row et al., 1981) took the analysis much further in order to calculate the overall economic impacts. They found that, even if a fully cost-effective substitute for the chemical were developed and made available within ten years and the best alternative methods were used in the meantime, the total impact of loss of the chemical on timber production would be about 940 million dollars. This is a staggering figure, but the impact of the use of this agent in timber production would not be recognized by simply considering the cost of its use versus the cost of alternative methods.

A similar case could be made for the development of an ASPAS system. The discussion in Section III of the benefits of such a

system centered on potential savings in the costs of spray operations, but the true value of ASPAS will be much greater when:

- the overall effectiveness of aerial spray is increased, and
- through greater accountability for the fate of sprayed chemicals, the environment can be adequately protected while at the same time overly cautious environmental safeguards are not necessary. In order to ensure that adverse environmental effects do not occur, a very conservative and cautious approach has been called for in many instances simply because of great uncertainty in the fate of applied chemicals.

In the course of development of the ASPAS, the product supplied and the delivery system will change considerably. As they do, the market they reach will change also as a consequence. The product will be improved in three clearly distinguishable aspects: the underlying mathematical models, the computer methodology used to calculate or solve the models, and the collection of data that are manipulated or produced. The data produced will not only be increasingly more accurate, but will consist of more relevant, easily interpretable information which is applicable to a wider range of situations. The software system used to manage and manipulate the models and data will become easier and less time-consuming to operate. The final delivery of the product to client pest managers and other specialists will come to rely not only on the presently-available methods but also on interactive summary graphical displays and field-oriented synopses. The market which is reached by these products can then be expected to grow as:

- reliability and precision of the outputs are increased,
- relevance and interpretability of the produced data are improved,
- the range of applicability of the system is increased to cover important pests, forest types, chemical formulations, and application equipment, and

- the system is used to make Forest Service environmental analyses better but easier,
- the accessibility of the system is improved.

The last of these points is primarily a characteristic of the delivery system. It should be stressed that the effectiveness of the delivery system depends not only on hardware, software, and publications, but on the personnel and organizational structure that makes use of these tools. Even improved tools would have little use without the necessary personnel to operate them and make them available.

The current system has been operated quite effectively by a system manager, an aerial application specialist, and some help contracted through specialists outside the Forest Service. Demands on the system can be expected to increase not only as the system is improved and widened in scope, but also as acreages subject to aerial pesticide application increase. This will likely occur as herbicide usage is increased, undoubtedly with greater requirements for supporting analysis than occurred in the past. In light of recent circumstances, spraying for gypsy moth control may also become more important since it has now been found in 26 states, with record defoliation. As the demand on spray planning systems increase, either the number of personnel involved will have to be increased or methods must be developed and implemented to facilitate information transfer to make more effective use of the personnel available. Suggestions to support this latter approach have been included in the plan for ASPAS development. In the MOD 1 and MOD 2 systems, mechanisms will be included to facilitate access to the system via remote terminals, operating over standard telephone lines. Changes proposed for the system software at these stages of development will allow easy control of the model and manipulation of accompanying data by field personnel with a limited amount of training. While

remote access will be practical at these early MOD's, changes outlined for MOD 5 will be necessary to support a large number of remote users. Perhaps more important for information transfer would be the development of field-deployable synopsis versions which could allow access to important model results by use of a portable calculator. This system would allow wide dissemination of information in a flexible, easily-used from which would not require multiple supporting personnel. The more conventional approach of publishing summary information in the form of tables or graphs could also be useful in some cases.

Organizational considerations concerning the ASPAS development must include the coordination of research and FPM activities. Adequate development of an ASPAS will require the participation of Forest Service researchers and researchers form other agencies. Several types of studies will be necessary, and much of the necessary work would most appropriately come from Forest Insect and Disease Research (FIDR). Cooperative projects with universities and other government agencies should also be sought. These should include Canadian organizations, USDA-APHIS, Agricultural Research Service (USDA-ARS), and U.S. military reseach organizations. For example, the U.S. Army is embarking on a significant program of chemical transport modeling. The Army Chemical Systems Lab and the Army Chemical School have recently funded sizeable research projects at the Atmospheric Sciences Laboratory (White Sands) involving transport modeling with terrain and vegetation effects. The Forest Service should capitalize on points of common interest and usefulness. It can be expected that such research will benefit from the direction and integration given by the model development process, which can point to weak links and gaps in the chain of knowledge necessary to produce a truly useful final product. On the other hand, a reliable and widely accepted model is likely to benefit from the expanded participation of the research community in general.

In summary: the plan for ASPAS development must be considered not only in view of the model itself, but in light of overall strategic concepts concerning the products produced, the market served, and the delivery system. The strategic plan for such a service organization has the best chance for success when it can be linked clearly and quantitatively to benefits for the intended clients. As the products are improved the market can be expected to grow, and the clientele will likely change. The ASPAS can be expected to benefit many more Forest Sevice programs, other agencies, state and even private industrial forestry. Environmental and methods development analyses can be expected to benefit, and research activities will both benefit and benefit from ASPAS development. Development of the model system will highlight research needs and justify specific research by pointing out gaps in our knowledgee of key components.

C. Specific ASPAS Model Enhancements Recommended

This section presents a number of specific improvements and supporting tasks which should be undertaken to bring the development of the current FSCBG model and program (MOD 0) to the level of the the MOD 3 ASPAS. These enhancements are those that can be currently recommended, in order to evolve the system to the degree which would be justifiable in light of the foreseeable needs of the system's users. The enhancements generally fall under one of the following categories:

- Program control,
- Input of data,
- Output and output format,
- Source characteristics,
- Wake modeling,
- Evaporation data and modeling,
- Details of the simulation process,
- Meteorology,
- Droplet impaction,
- Biological effectiveness,
- Environmental hazard estimation, and
- Model fitting and validation.

Important points concerning interdependencies and priorities are discussed in the following list where appropriate. The order of the list does not necessarily reflect the importance of the points, but does reflect interdependence and timing considerations as will be seen in Section V, which outlines the research and development plan.

- Deposition Calculations for All Heights Simultaneously. As the FSCBG program is currently structured, deposition and dosage calculations are output for one level at a time. Data describing an entire height profile through the canopy should be made available.

- Simplified Input of Droplet Spectra. Droplet size categories and the distribution of spray mass among them should not have to be input by the user for each program run. They should be stored by the system for later call-up based on aircraft type, spray equipment, and formulation.
- Simplified Input of Stand Description Data. The parameters describing the structure of the forest canopy should not have to be input by the user for each program run. They should also be stored for later call-up. The system may initially only contain stand descriptions for a few scenarios, but a data base should be developed to allow selection of the necessary parameters for canopy description based on a simple stand classification system.
- Summary Display Programs. An interactive graphical display program should be developed to allow easy selection of displays based on data stored at the completion of a model run. The available displays should include profiles at specified points and contour diagrams of deposition, maximum concentration, dosage, and eventually target pest mortality. Even before the target pest mortality modules become available, this system would allow a 'man-in-the-loop" approach to be used, allowing an expert to make mortality estimates based on a summary of pesticide distribution within the canopy. This system could be used to allow a manager to find a good prescription for application parameters by interactively evaluating displayed information based on his knowledge of what he has available and the accompanying costs. He would also easily obtain a

feel for the sensitivity of the results to the factors under his control. Development of summary display programs would necessitate the performance of calculations for all heights in the canopy simultaneously.

- <u>Interactive Program Control</u>. The basic simulations performed by the APSAS will be performed by a batch program, but the setup of the program for a particular run and the control of generated output (discussed above) could be handled by interactive routines. The program setup software could be visualized as a program which creates the input deck for the main simulation program. It could do this by asking the operator a series of questions which would indicate which simulation options were desired and which data are to be used. Call-up of existing data files would be facilitated by the input data generation routines described above for droplet spectra and stand descriptors. The software should also allow entire sets of input data from previous runs to be recalled, any parameters changed at will, and rerun. If major subsets of the data do not exist in the data base then the operator should be able to ask for an input prompting routine.

- <u>Effective Wind Speed Correction</u>. The Barry-Grim canopy deposition model is based on the assumption of a constant wind velocity at any given height within the canopy. In reality, winds within a forest canopy ordinarily vary significantly over both time and space. The effect of varying wind velocities should be considered in the prediction of impaction efficiencies, as noted by Bergen and

Waite (1976) in a study involving paired-cylinder collection devices. This is because the impaction efficiency varies approximately as the root-mean-square of wind speed. Consequently, although average wind velocities may be adequate to describe the ballistic trajectory of droplets, a correction factor should be introduced to the impaction model to account for non-uniformity of the wind velocity.

- Improvements in the Impaction Model. The Barry-Grim canopy penetration model as it is now implemented relies on Sell's Law to describe the impaction of spray droplets on foliage elements. The impaction model should be revised to take advantage of other experimental and theoretical results, for example those reviewed by Golovin and Putnam (1962). The resulting routine for predicting impaction efficiency should account for the various geometries of vegetation elements, including hardwood leaves.

  The inadequacy of Sell's Law has been pointed out in a Forest Service study of the behavior of sprays against the spruce budworm. This work has shown that small particles are observed on larvae even though Sell's Law says that their impaction efficiency should be very low. "The fact that small particles were observed on the larvae suggests that another unknown mechanism or combinations of mechanisms are causing impaction or deposition of particles on the budworms and Douglas-fir needles" (Barry, Ciesla, Tysowsky, and Ekblad, 1977; Barry and Ekbld, 1978). This factor would also explain Picot and Kristmanson's (1980)

poor fit for small droplets. An improved but still basically theoretical impaction model such as one based on Golovin and Putnam's study would likely give an improved fit, but some potentially important factors, such as surface effects of roughness or adhesion or electrostatic effects, would still be unaccounted for. An accurate representation will have to be based upon experimentation. This is discussed further in a succeeding paragraph.

- Test Evaporation Routine Using Existing Data. The evaporation module of the current FSCBG program should be validated by studying the conformity of model predictions to available field study data. The data generated by the Withlacoochee State Seed Orchard spray trial (Rafferty et al., 1981) would be suitable for this purpose, and data from a recent Kaibab National Forest study using orthene in water would also be appropriate (J. Barry, D. Parker; personal communications, 1981).

- Alter the Program to Allow Model Runs With Any Flight Pattern. This should be a simple modification. The program can already describe various patterns of flight lines on a horizontal plane, but the altitude should also be allowed to vary from one line to the next. This would allow analysis of some different cases, for example: 1. What is the effect of lowering the flight altitude of the most downwind pass over a spray block, in an effort to avoid off-site drift? or 2. Would deposits be more uniform on the up-wind edge of a spray block if the altitude were lower but the flight lines were closer together?

- Alter the Simulation to Allow Forest Edge Effects Beyond the Canopy. The current canopy penetration simulation module assumes that the structure of the stand is quite homogeneous over the area of concern. This is not an unreasonable assumption for the calculation of desired buffer zones along small streams, etc., but a fairly simple alteration of the simulation would allow a more accurate representation of edge effects such as could be expected along the shoreline of a lake. The simplest alteration would be to allow the canopy to stop (or decrease) at some boundary line. The wind velocities could also be allowed to change at the boundary, and the vegetation density could be allowed to increase at the boundary.

- Deposition Accounting by Tree Type. The canopy penetration simulation module would be more generally useful and flexible if deposition were accounted for separately by tree type. This may be necessary for the development of mortality prediction models for some insects, which may attack one tree type over another or behave differently on one tree than another. The pest manager may also wish to protect one species of a tree rather than another, or he may aim herbicide applications at one type of tree.

- Slope Correction for Canopy Penetration. Although the current canopy penetration model does not include an explicit representation for sloping topography, this in itself is not of great consequence. This is because even on steep slopes the winds generally follow the contour of the

land, so that a droplet requires the same amount of time to fall to the ground from the top of the canopy (assuming a simple laminar flow) regardless of the incline. Height in this case must simply be interpreted truly vertically rather than as the distance normal to the ground. However, the angle of attack of droplets passing through the tree envelopes will not be accurately represented in the present simulation. A correction for this could easily be added to the program.

- <u>Improved Fitting of Impaction Coefficient and Probability of Penetration</u>. The FSCBG program has been changed since the probability of penetration and impaction coefficients were originally fitted. The calibration of the model with respect to these parameters should be re-checked. The data from the Withlacoochee seed orchard spray trials or the Kaibab National Forest project should provide an adequate basis. Calibration of the penetration and impaction aspects of the simulation should only occur after Sell's Law has been revised and any appropriate effective wind speed correction has been made.

- <u>Near-Site Drift Measure of Hazard</u>. One or more explicit measures of the hazard of the applied pesticide to non-target organisms in and near the spray block should be incorporated in the program. This could consist of very simply calculated measures, for example relating the LC_{50} (concentration lethal to 50 percent) of an aquatic species of concern to the concentration expected to be deposited in a 10 inch deep pool of water.

- Herbicide Measure of Effectiveness. A measure of effectiveness (MOE) for herbicides should be made an integral part of the program, in order to provide an explicit criterion for judging the value of spray distributions. This could involve a percent kill (with given probability) or similar measure of effect on target species. Such a measure is necessary certainly for any attempt to optimize aerial spray characteristics (subject to any constraints identified by the measure of environmental hazard), but it would also provide a focal point to guide judgements during system development, including supporting data, research, and program module characteristics. Biological measures of effectiveness are discussed elsewhere in this report. Development of a general module for estimating herbicide MOE's will require the previous development of a deposition accounting scheme by tree type, and for all heights in the canopy simultaneously.

- Simple Insecticide Measure of Effectiveness. The modeling of the biological interface as it relates to insecticides is also considered elsewhere in this report. An MOE for insecticides is needed for the same reasons that an MOE is needed for herbicides. However, the form of the MOE need not be the same. An estimate of a percentage of target insects expected to be killed at a given probability appears to be a goal attainable in the near future on the basis of quite simple models. This will of course require that deposition be accounted for at all heights in the canopy, and in some cases also by tree type.

- Sensitivity Analysis. A sensitivity analysis should be undertaken to determine the influence of changes in input data and parameters on the outputs of the model. This analysis should not be undertaken until the enhancements listed above have been completed, especially the introduction of measures of effectiveness for herbicides and insecticides and the introduction of an explicit measure or measures of environmental hazard, since these outputs would be the most appropriate ones for investigation. This analysis will help the user decide which inputs should receive the most attention. It will also act as a test on perceived priorities during model development. The sensitivity analysis will have to be evaluated in the light of all assumptions that were made during model development, since the technique assumes that the structure and all functional relationships of the model are assumed to be correct. Any conceptual errors present may lead to spurious results (van Keulen, 1976).

  A simple perturbation approach (which can make use of analysis of variance techniques, as for example Steinhorst and others, 1977) should be followed, since it can be expected to reveal the most important aspects of the behavior of the system if applied in the region of concern within the parameter space. The analysis should be repeated for several scenarios, representing the most likely situations for application. The parameters should be perturbed singly, and one the basis of those results, in selected combinations. This approach should be relatively economical. Although more

complete approaches are available, for example, based on the sensitivity theory of Tomovic (1963, 1970), they are generally unweildy and uneconomical for models of this size. Whenever significant changes to the model structure are made in the future, they could be followed by a sensitivity analysis which considers relevant parameters.

- Aerial Spray Mission Cost Computation. Finding the best prescription for an aerial pesticide application project depends upon a knowledge of the costs of the various alternatives, as well as their expected benefits. The availability of a computer program to facilitate cost computations should be considered a requirement of the ASPAS. However, this program need not be part of the ASPAS software itself, but could be a separate program. This would probably be the best approach, since the cost calculation program will appeal to a wider set of users, and requires substantially different input information than the ASPAS proper. A procedure to perform mission cost calculations has been developed by the Missoula Equipment Development Center, the details of which are in press (Ekblad, pers. communication).

- Interim Documentation. New documentation should be produced at a point where the most immediate enhancements have been made to the system and a sensitivity analysis has been performed. The documentation should describe all significant model modifications, but should be complete in itself (being built around the existing FSCBG documentation). This new documentation should describe a completed generation of the system (MOD

1), which is ready for general use. A simple, smaller document should also be produced for people in the field informing them that the system is available, what it is, and how to make use of it.

- <u>Research Data on Modes of Toxicity</u>. As discussed elsewhere in regard to the biological interface, the modes of toxicity of important pesticides to their target pests must be elucidated before their relative contributions to mortality of the target can be assessed by means of an improved mortality model. Research should be undertaken to acquire the necessary data. This data will indicate among other things, whether inhalation toxicity is important, and consequently if prediction of aerial concentrations and dosage within the canopy would be useful.

- <u>Droplet Spectra Data</u>. A knowledge of the distribution of droplet sizes produced by a spray system is basic to any attempt to predict spray cloud behavior and fate. This type of data are needed for all sources to be considered by the model, so initial efforts should concentrate on the most commonly used aircraft, spray generation equipment and formulations for which the data are not already available. The increasing amount of data will be more easily handled by the routine described above for source data storage and call-up. Research groups in the U.S. and Canada have been developing data on droplet spectra at nozzles in wind tunnels, and also in field experiments. For example, work is currently being done at the University of California at Davis using lasers to

characterize sprays from various nozzles. This work should be continued with high priority.

- Additional Foliage Distribution Descriptions. The stand description input data generation routine called for in an earlier paragraph will make the handling of such data easier, and will lend itself to the archiving of the necessary data. The program will then be able to store internally all the information (it could be in the form of equations or tables) needed to represent the whole range of stand configurations over which the model is to be applied, including hardwood forests and conifers with hardwood understory. Some information is already available in the literature to support this work. For example, Storey, Fons, and Sauer (1955), and perhaps others, have developed regression equations for both coniferous and hardwood foliage, involving DBH, live crown width, dry foliage weight by height, etc. The work necessary to collect and organize such data could be considered in three stages; (1) to survey the literature in order to identify relevant studies, (2) to develop an appropriate stand classification scheme for the purposes of the model (with the objective of easy use by field personnel), and (3) the collection of necessary data which could not be found in the literature.

- Improved Wake Model. The wake model presently used in the FSCBG computer program is a simple empirical model developed as a description of patterns seen in aerial photographs of spray releases over a forest canopy. The developers of the program have pointed out the limitations of

this model (Dumbauld, Barry; personal communications, 1981) and the recent Withlacoochee spray trial study has confirmed that the wake description is a major weakness of the model system. Upgrading it should be a high priority. A wake modeling study has been funded by the Forest Service's Missoula Equipment Development Center through NASA's Langley Research Center. This work involves a private contractor: Continuum Dynamics Inc. of Princeton, N.J. However, this work to date has not been aimed at describing the behavior of wake vortices over forest canopies. The modeling effort should be expanded to account for canopy interactions.

- Simplified σ_A and σ_E Input. The variations in wind direction represented by σ_A (the standard deviation of wind azimuth angle) and σ_E (for the wind elevation angle) are not observable in the field with simple equipment. A method should be devised to estimate these required input data, based on more easily obtainable information. For example, σ_A and σ_E might be estimated from a stability class, which could be derived from simple measurments (which might be obtained from a nearby airport) including the wind speed, wind direction, cloud cover, and time (K. Dumbauld, personal communications).

- Simplified Wind Profile Generation. Description of a complete wind profile through and above a forest canopy requires instrumented towers or sophisticated meteorological gear. A method should be devised to derive wind speed profile estimates from data easily obtainable by field

personnel. The output data required by the model could be related to meteorological information obtained from nearby weather stations and/or some simple wind speed measurements taken on site, along with data describing the stand and topography. The method should be based upon studies already available in the literature e.g. "Some Measurements of the Adiabatic Wind Profile Over a Tall Irregular Forest" (Bergen, 1976) and "Vertical Profile of Windspeed in a Pine Stand" (Bergen, 1971). Other studies can be found in an annotated bibliography by Robert Baughman (1981). This task should be coordinated with research now being conducted for the U.S. Army at White Sands (Atmospheric Sciences Lab).

- Persistence and Photodegradation Module. Certain pesticides, especially some of the biological agents, degrade quite rapidly after being deposited in the field. Degradative processes do not occur equally throughout the canopy, and can even be expected to differ from top to bottom of a leaf. Washoff by rain can of course be an important factor, as well as hydrolysis and other chemical reactions. However, photodegradation is often of primary importance and it is a factor which is expected to vary through the canopy in a fairly predictable way. The amount of sunlight penetrating to different levels in forest canopies has been examined in studies of photosynthesis and energy relationships. Based on this literature the stand structure information already required by the model could be used to estimate rates of degradation at various points within the canopy.

This information would be of most use to the module which predicts insecticide effectiveness, and it may help to explain some of the variability in mortality observed with some pesticides.

- Dosage Prediction Within the Canopy. The results of research into the modes of toxicity of important pesticides will determine whether or not a prediction of dosage (concentration integrated over time) or peak concentrations below the top of the canopy are necessary. This module should be considered unneccesary unless research indicates that inhalation toxicity is of considerable importance. There is, moreover, no model available at present which can make predictions of pesticide inhalation with any confidence. Improvement and validation of gradient transfer models (such as those under development in New Brunswick by Picot, Kristmanson, and others; 1980 and 1981) or perhaps another approach could lead to the development of a module for this purpose. Research into the nature of airflow within the canopy may eventually allow a more advanced model for dosage prediction.

- Routine to Adjust Model Predictions Based on Field Managements. Spray projects typically include some monitoring of spray droplet deposition at least at ground level. If these deposits differ appreciably from what has been predicted by model calculations then a procedure should be explicitly built into the program to allow an adjustment of deposition predictions to reflect these data. This could be a very simple procedure which distributes the observed error within the canopy, assuming that the prediction at the canopy top was correct.

This will then allow a revised estimate of target pest mortality to be made as part of a posterior evaluation. If quick-turnaround times were supported, then short-term adjustments could even be made on site, perhaps between blocks. Monitoring of mortality or pest population levels is also often performed after spray operations. The data collected in these cases could be very useful as a source of longer-term feedback for model adjustments and improvements. Consequently, both deposit monitoring and bibliogical monitoring data should be maintained along with corresponding model predictions in a systematic database.

- <u>Empirical Impaction Model</u>. The theory of impaction has not been developed sufficiently to accurately represent all of the factors relevant to forest pesticide spray behavior. The inadequacy of Sell's law has been discussed in a previous paragraph, which also pointed out that even an improved representation of inertial impaction, such as could be based on the publication by Golovin and Putnam (1962), would leave some important factors unaccounted for. Consequently, impaction could best be predicted based on experimentation. For example, wind tunnel experiments have been conducted and have generated relevant data. They have been conducted in Canada as well as the U.S., e.g. "Particle Deposition in a Douglas-fir Canopy" by Wedding, Carney, Ekblad, and others (1977), who examined deposition not only on foliage but also on target insect larvae. This kind of approach could account for much of the micrometeorological effects, electrostatic

effects, and surface effects of roughness and adhesion. Irregular target geometries, such as hair-covered caterpillars would also be accurately reflected by an empirical relationship, although they could not be easily represented theoretically.

A wind tunnel model could be used not only to generate empirical impaction data, but also to observe the target insect mortality which results from a given pattern of droplet deposition. Such a physical simulation would integrate most of the factors which the model needs to consider from the time droplets reach a given tree, including the probability of penetration, impaction, and mortality resulting from a combination of direct or indirect contact, ingestion, and inhalation toxicity. While field experiments could produce some of the same information, the component factors could be much more easily controlled and their effects separated by means of wind tunnel simulation studies. Consequently, it is strongly recommended that such studies be undertaken to allow empirically-based predictions of these effects to be made, resulting in mortality estimates for important pests on their most common hosts.

- <u>Mesoscale Model Interface</u>. The structure of the FSCBG model is not adequate for the analysis of long-range drift, although the current system could and should be used to investigate the magnitude and nature of near-field drift. Long distance drift analysis often requires a consideration of the effects of topography. Mesoscale meteorologi-

cal models have been developed which are capable of representing topographical effects on a wind flow field at the necessary scale. Some of the applicable models have been reviewed by Bergen (1979). EPAMS (Dumbauld and Bjorklund, 1977) was probably the first model to combine a mass consistent flow field with a plume model. This scale of modeling is currently of interest to the U.S. Army.

An appropriate mesoscale model should be chosen and an interface should be designed to enable an application of the ASPAS to generate data (droplet and vapor distribution) for input to the mesoscale model. This interface could require alterations to either the ASPAS itself and/or the mesoscale model. The mesoscale model itself should also be modified if necessary to produce appropriate measures for environmental hazard estimation.

Where complex terrain effects on cloud trajectory are not important, a simpler model such as that developed by Reid and Crabbe (1980) could be used, but the development of an adequate mesoscale model would make the inclusion of a simpler model unnecessary, since level topography can be considered as a special case of the more complicated situation.

The required accuracy of a mesoscale model should be considered separately from that required on-site. In estimating environmental hazards due to drift, it would be preferable to err on the high side. But in estimating the amount deposited on target, it would be preferable to err on the low

side. The required accuracy is also probably greatest for on-site deposition. These requirements are consistent with a configuation coupling the ASPAS with a mesoscale model such as EPAMS.

A shortcoming of the FSCBG at present is that all of the chemical which enters the canopy is assumed to remain there. This does not account for dispersal of vapor and small droplets of the chemical back into the atmosphere. This ventilation effect should be considered at least as it impacts offsite drift. Onsite effects are not expected to be influenced significantly by this phenomenon.

- Improved Insecticide Effectiveness Module. The improvements discussed in the paragraphs above, along with research aimed specifically at the biological interface, will make revision of the insecticide effectiveness module appropriate to best exploit the potential capabilities of the second generation ASPAS system. Details of the biological interface development are discussed in Section IV-D.

- Model Validation. Validation of the model by carefully planned field trials will be a necessity. The testing should be considered in two phases: calibration and validation. Calibration is a process of fitting the model to observed data. In this phase, relatively poorly known parameters can be adjusted if necessary in order to improve the correspondence of the model with the observed data. Relevant historical data could

be used for this purpose, as well as the initial field trials. Subsequently, the model can be truly validated by showing that it can handle independent data under various conditions. The principal objective of the model is to summarize and predict, but the requirements for validation depend on the uses to be made of the predictions. Verification of model outputs must be related explicitly to the purposes of the end users. One purpose of validation should be to demonstrate to potential users of the information that it is superior to subjective techniques. Testing of the model should occur at key points to trouble-shoot new model improvements. Its timing should be planned carefully to make efficient use of the data, and to avoid unnecessary expense.

- <u>User Documentation</u>. User documentation during the early phases of system development should be aimed primarily at FPM specialists. It should address the theory of the model in a general and easily understandable way, and clearly outline the proper manner of use and interpretation of output of the system. This document should enable a qualified specialist to operate the system without reference to any other sources of information. It should include an appropriate example problem.

- <u>Maintenance Documentation</u>. A document should be produced for the system manager and any analysts and programmers who may be involved in system development or maintenance. It should encompass the theory of the model (in a more complete manner

than the user documentation), the overall design of the software system, details of the coding, and listings of the source code.

- Empirical Evaporation Descriptions for Major Formulations. The FSCBG program currently includes three methods for modeling evaporation from spray droplets. The theoretically based techniques are not sufficiently accurate and easy to use to represent diverse tank mixes. Consequently, equations which are empirical descriptions of experimental evaporation data are the most generally useful approach at this point. The Missoula Equipment Development Center has sponsored some studies which have measured changes in drop size over time. This type of work should be continued to include all major formulations.

- Spray Adjuvant Effects. Spray adjuvant are widely available and used, and they are recognized by many users as important modifiers of aerial spray behavior. However, their effects on droplet spectra and evaporation are not understood. Consequently, data collected on droplet spectra and evaporation should include formulations with spray adjuvants in order to ascertain their effects. An analysis of the resulting data should be carried out to ascertain whether the effects of the adjuvants are predictable for various formulations, and if so to internalize his information in the model. This would allow the program to automatically correct the droplet spectrum and evaporation description based on the adjuvant content.

- Synopsis Versions for Portable Calculators. If ASPAS is to be successful, all aspects of its design and development must be aimed at providing the user with the most useful possible information in a conveniently useable form. The user must not only be given the information he wants, but he should not be given information he considers unnecessary. The information would be most useful if it were made available by a portable, field deployable method. Techniques traditionally used under such circumstances include handbooks, printed tables, and nomograms. More powerful and effective methods are now possible as a result of the introduction of inexpensive and easily portable calculating devices.

  The ASPAS system should make use of a portable calculator to summarize outputs of interest in specific applications for selected scenarios. A synopsis version for a particular application would certainly have to be less powerful than the programs operated on the mainframe computer, but could present the outputs of most interest based on a subset of the input data representing items which are relatively important, are expected to vary significantly from application to application and are easily identifiable in the field. The inputs required by the synopsis versions need not be from among the same items required by the main program. The synopsis input may contain a set of "proxy" variables which are used to indicate the actual variables which are required in the simulation. For example, "early morning, calm" may be all that is required to specify the necessary meteorological variables.

The development of synopsis versions will require:

1) A selection of specific situations and objectives for synopsis development, in light of ASPAS capabilities at that time and an appraisal of Forest Service pest management activities and prospects.

2) A determination of the best way to extract the required information from the main model. This may include model simplification, creation of a data base summarizing relevant results, or development of summarizing equations by regression or another technique.

3) Selection of appropriate hardware considering cost, ease of use, portability, reliability, display capabilities, external data storage and transfer capability, memory capacity, and computational ability.

4) Actual implementation and coding. This should be done in a manner which allows easy use by personnel who are not familiar with the equipment or the programming.

- Synopsis Documentation. Specific documentation should be created for each synopsis version developed. It should include step-by-step instructions for orientation and training of field personnel. It should give only a very brief account of the theory, but should contain guidelines for model use and interpretation of results.

- Parameterization of the Monte Carlo Simulation. The Barry-Grim Canopy Penetration Model is based on a Monte-Carlo simulation technique. This would

require significantly less computer time to run if it were instead parameterized. However, this project should not be undertaken unless prospective savings will be well worth the investment. At this time, it appears that it should be given low priority in the near future. The possibility should be re-assessed after the first couple of generations of the system are developed.

- Adaptation of a Crop Canopy Deposition Model. Aerial spraying of herbicides and to a lesser extent other pesticides in forest management often occurs over sites without well-developed canopies. Herbicides are often sprayed over short canopies and fairly open areas for rangeland improvement, regeneration, and release purposes. In these cases the application of a forest canopy penetration model is not necessary. For high-level flying, the existing model structure is adequate for those situations and should only require adjustment of the penetration model. Over open rangeland, the penetration model is not necessary at all. However, for low-level flying the current model is inadequate since the interaction of the aircraft wake with the ground and the vegetation is the dominant factor. These situations are similar to those encountered in applications over agricultural row crops. Models applicable to these situations have been developed. For example, the NASA Langley Research Center has sponsored both theoretical work and physical model studies, and mathematical models have been published by Miller (1980), Bache and Sayer (1975), Bache and Uk

(1975), and Bache (1975). Empirical studies have been carried out at the University of California at Davis by Akesson and Yates, and others.

The applicability and adaptability of available models to the ASPAS system should be studied. If a model is identified as being appropriate, then it should be used as the basis for creation of a new module for prediction of deposition and drift over low vegetation during low altitude application. While this module would be useful to the Forest Service, it would also make the system very attractive to other users such as USDA-APHIS who are concerned with agricultural spraying.

- Synopsis Version of Open Area Module. If, after the development of a module for areas with low-lying vegetation, prospective use seems to warrant it, then one or more synopsis versions should be developed and doccumented.

- Further Validation. Important changes or additions to the model system, such as the development of a module for open areas and low-lying, vegetation, should be followed by experimental verification, as discussed above under Model Validation.

- Update User and Maintenance Documents. Major changes to the model system must also be followed by an updating of the accompanying documentation. Maintaining current documentation can be costly, time consuming and confusing to the user. In order to avoid such problems as much as possible, the documentation should be planned together with the system development, and should be organized into discrete, readily identified generations.

D. Biological Effectiveness Module (BEM)

In its July 1979 report, the Forest Service Aerial Application Technology Workgroup described the need for better methods of estimating the spray deposit/mortality relationship as follows:

> "A lack of information on the relationship and interaction of the pesticide, environment, weather, and host to the target pest has resulted in pesticide field experiments, pilot projects, and operational projects with highly variable results. This phenomenon is particularly true with biological agents. Advances in aerial application technology are hindered by this lack of information."

This interface between aerial application technology and the biological effects of the spray on target pests is a key element in the development of an ASPAS system. Current spray deposition model outputs must be linked to expressions of mortality, either absolute or relative, if they are to be truly useful in aerial spray program planning. In the current MOD 0 configuration, a gap exists between the simulation of physical forces affecting spray droplet deposition on or off-target, and the planning functions required of effective program operation. Examples of such functions are:

- control program planning,
- fiscal planning and budgeting,
- research planning and prioritization, and
- environmental impact mitigation.

Feedback functions are also served by incorporating mortality expressions in the ASPAS sytem, thus allowing a measure of effectiveness in the evaluation of program performance. Bridging this gap requires activity in two distinct areas.

- Enhancement to the FSCBG program which will facilitate linking with a biological effectiveness module.

- Development of the biological effectiveness algorithms.

Those enhancements to the FSCBG program itself which are required (including deposition calculations for all heights within and below the canopy and deposition calculations by tree types) are discussed in detail in Section IV.C of this report dealing with FSCBG enhancements. A third area where enhancement is liable to be required is prediction of dosage below the canopy. As is discussed in the following sections, the need for this particular capability has yet to be fully determined, as it is a function of the outcome of required basic research.

1. Measures of Effectiveness (MOE's)

In taking the systems approach to developing an ASPAS system, MOE's must be defined which are both comprehensive and meaningful. Well defined MOE's serve two principal functions in systems design. First and foremost, by specifically identifying requirements ahead of time, they help to ensure the availability of necessary data at the decision-making point. Secondly, they allow the quantification of nebulous concepts (indeed, they demand it) in consistent, meaningful terms. In terms of aerial spray program planning and analysis, well defined measures of effectiveness will provide a focus for gauging system performance, as well as providing in a relative sense criteria for comparing alternate application scenarios.

A number of possible measures of effectiveness have been examined in light of the objectives and evolutionary nature of the ASPAS system. These include:

- target pest mortality (plant or insect),
- changes in program costs (marginal costs and benefits),
- increased product growth (or stump life in the case of insect pests),
- increased economic value, and
- increased productive capacity of fixed resources.

Clearly, as the ASPAS system evolves over time so too must the MOE's. At this point (MOD 0) and likely into MODS 1 and 2, target pest mortality is the single-most meaningful MOE for the proposed ASPAS system, and hence is discussed here in considerable detail. Others which can be expected to be of future benefit are discussed relative to future modifications to the system. They mainly involve combinations of more than one of the above which should also be considered. The most promising combination is of course that of the first two whereby estimates of target pest mortality are further translated into changes in application program costs, quite likely through linking with the MEDC mission economics model.

Closely related to the development of MOE's is the issue of spray program objectives. A need exists for the quantification of these objectives, e.g. an expression of objective mortality which is a function of pest population density. This system need not be elaborate by any means, perhaps simply a graduated scale expressing percent kill (with larger percentages for larger populations, resulting in the same numbers of survivors per unit area regardless of original population size). Each control program has either explicit or implicit mortality objectives. For example, an eradication program has the objective of 100 percent mortality (or a high enough percent to prevent population recovery). Many forest pest control programs have the implicit objective of 60-95 percent mortality, the explicit objective being to keep trees on the stump until harvest is possible. Whatever the objective, it must be quantified and would preferably be expressed as a function of pest population size, or in terms similar to any selected MOE's.

2. Target Pest Mortality Estimation

Very few attempts have been made in terms of developing models of the biological effectiveness of pesticide sprays. This appears to be due in large part to the complexity of the effort, and the degree to which the many interrelating factors are

understood. For each individual insect pest, for example, there may be a number of intrinsic and extrinsic variables each of which impacts upon spray toxicity in its own right, and through interactions with other variables. For most insect pests it is entirely possible to identify the intrinsic and extrinsic variables, but almost impossible to determine with any degree of certainty, precisely what the effects of each, singly and in combination, will be in terms of spray toxicity. Adding to the apparent complexity are those factors affecting the nature of the toxicant itself after delivery to the target such as volatilization, photodegradation, and others. Finally, the issue of the transition from estimation of individual pest mortality to that of population effects has not received widespread attention and yet its importance cannot be understated.

Given that the individual and combined effects of intrinsic and extrinsic variables are not well enough understood to allow a classical analytic solution, three alternate avenues of target pest mortality estimation have been examined. These are: development of a computer simulation model, development of probabilistic mortality models, and regression analysis of existing or generated trial data. Care must be taken at the outset to properly define what is meant by these approaches. An analytic approach is used here to mean one whereby the overall behavior of the system in question is directly described by a deterministic, mathematical model. In order to utilize this particular approach it must be possible to construct a mathematical model that is a reasonable idealization of the problem, and which is amenable to solution. Simulation on the other hand is used to describe the approach where the operation of the system is described in terms of individual elements. Probabilistic models are simply considered a subset of system simulation where system elements are described in terms of probability distributions. Finally, regression analysis implies the standard

order for this to be accomplished, alterations to the FSCBG program to allow for deposition predictions for all heights within the canopy simultaneously, as already discussed, must of course be undertaken. In addition, further investigation into the distributions of target species within the canopy in terms of both the physical distribution of individuals within the canopy, and the life cycle stage distribution over the population which is already accounted for in the model is necessary.

With respect to application of the model to herbicide treatments, the model should be simplified to account for both the sessile nature of the target, and for the different response to toxicants (e.g. no genetic resistance, etc.). Other model enhancements already noted with regard to insect pests also apply here, namely expression of outputs in terms of probability distributions, and applicability to different tree heights simultaneously. This is particularly important with respect to hardwood species which are distributed at all heights within the canopy. A more sophisticated, yet likely feasible in the short term, addition is the development of a response index similar to that recommended with respect to insect species genetic response. Again, this need not be an elaborate physiological response modeling effort. The objective is to produce a series of indices which indicate <u>relative</u> responses to herbicide treatments of the various economically important plant pests. Development of these indices can be accomplished through either physical simulation (e.g. wind tunnel tests) or through analysis of existing program data, if such data proves sufficient. These indices of expected response of plant species would then be essentially "tempered" by the variables and associated probabilities of the simplified mortality model.

3.2 BEM Development: Phase II

Phase II development of the BEM should proceed along a number of fronts simultaneously with the end objective being the

development of a reliable BEM which can be incorporated into future MODs. These different fronts include the following.

- Enhancement of the manner in which factors already accounted for by the Force et al. model are handled.
- Investigation of and possible inclusion of additional factors impacting efficacy.
- Extension of the model to additional pests and pesticides.

Points relevant to each of these three 'fronts' are discussed in the following paragraphs.

3.2.1 Improved Detail for Currently Utilized Variables

Each of the variables currently utilized by the Force et al. model uses combined normative/quantitative estimates of likely outcome. To the extent possible these event outcomes need to be expressed quantitatively based upon existing and 'to be generated' data. For example, insecticide dosage estimates are based upon the assumption of 80 percent loss at tree level, and possible events "bracket" this figure. Adaptation of these possible outcomes to receive FSCBG output will result in much more accurate portrayal of dosage. Using FSCBG simulation runs it would be possible to construct probability distributions describing dosage for use by the BEM.

A second factor which should be altered is the genetic response factor. Studies conducted by Stock and Robertson (1979) on forest defoliators have clearly demonstrated the variations in genetically - mediated response characteristics of these species, both among and within populations. Measurable variations occur between populations over relatively short physical distances. These studies have also demonstrated that genetic response is a key variable in the estimation of target mortality as a function of spray deposit. In fact the model developed by Force et al. includes this as the primary intrinsic factor considered. In

utilizing this factor one must first conduct a prespray genetic survey to determine expected response. Through the use of physical simulation (e.g. wind tunnel testing) the expected response of different populations can be estimated or characterized such that an index of expected response could possibly be substituted for prespray surveys. Such an index would indicate the type of expected population response (e.g. tolerant, susceptible, resistant) for various subgroups within a pest population. Essentially this would entail work almost identical to that conducted in a prespray survey, the difference being that it would be conducted for many populations at the same time via physical simulation. Such advance indications of probable response is necessary if program planning is to be conducted early on.

As already noted, in addition to data on the instar distribution through the population which is already accounted for in the model, more information is necessary concerning the physical distribution of insects throughout the canopy. Pesticide deposition can be expected to vary within the canopy, hence so too will delivered dosage. The implications of this upon target mortality need to be investigated, and if prominent, incorporated into the model.

Finally, type of exposure is an area which is not well understood, and knowledge of this factor should be upgraded. Exposure may result from feeding, inhalation, direct contact, subsequent contact (e.g. walking over), or any combination. The relative importance of each needs to be determined in terms of contribution to mortality so that effective droplet size, desired deposition characteristics, etc. can be determined. In short, very basic research is needed to identify those modes of toxicity exerting the greatest influence upon eventual mortality. Once identified those modes can be studied in-depth relative to each

species in order to determine the extent to which it can be accounted for in the BEM, and the manner in which that should be done.

3.2.2 Additional Factor Identification and Analysis

The Force et al. model currently considers the following variables.

- insecticide dosage,
- genetically determined response characteristics,
- instar distribution
- type of exposure
- moisture condition of the foliage,
- rainfall, and
- presence or absence of larvae.

All additional factors impacting on insecticide efficacy need to be identified and investigated with an objective of determining the relative importance of each. Such additional factors may include: additional details concerning the physical features of both target and host species; factors describing the relationship between target and host species; physical and chemical effects on spray droplets after deposition such as volatilization, photo-degradation, etc.; droplet distribution on the leaf surface; temperature effects and others. The objective here is not to develop an inordinately complex model, but rather to develop a probabilistic model which strikes the desired balance between output accuracy and model complexity. Should any of these factors prove to have a substantial effect upon insect mortality they should be incorporated into the model as appropriate. Once so incorporated it would be an easy task to conduct limited sensitivity analysis over all factors in an effort to keep the model as simple, yet reliably accurate as possible.

3.2.3 Extension to Additional Pest Species

The value of the Force et al. model, or any alternative model, for incorporation into the ASPAS system

depends on its applicability to a variety of pest species. This is of course why a general approach was selected as opposed to a more sophisticated, mathematical model. In its current state the model is applicable to two pest species, the western spruce budworm, and the Douglas-fir tussock only. To be appropriate to future system MODs, capabilities will have to be extended to additional pests. At the present time it would appear best to include two additional species, the eastern spruce budworm, Choristoneura fumiferana and the gypsy moth, Lymantria dispar L. In including additional pest species the principal area of activity is the determination of genetic response for the species. This should not be confused with identification of response variations within a population discussed earlier. Considerable time and effort (½ man-year over 1 calendar year minimum) will be necessary in order to determine the expected response characteristics of additional species. Experimental use of the model for the two species already incorporated has demonstrated the importance of the genetic response factor in estimating pesticide efficacy, hence expected response of additional species must be fully understood prior to field application of the model.

3.2.4 Model Validation

Upon completion of the above efforts, including additional pest capabilities, the model should be tested against both existing control program data, and large-scale field trials. It may be possible to substitute physical simulation for program data to a certain extent. However, actual field studies are needed to demonstrate capabilities, identify errors, etc. prior to incorporation into the ASPAS system. Such field trials would of course be integrated into those necessary for the validation of other system components discussed elsehwere.

SECTION V

RECOMMENDED RESEARCH AND DEVELOPMENT PLAN - MANPOWER ESTIMATES

The purpose of this section is to outline a plan for the phased implementation of the specific enhancements recommended in the preceding section. Figure V-1 is a flowchart showing the improvements recommended to bring the development of the system from the current MOD 0 to a complete MOD 1. The flowchart also shows suggested interrelationships among the tasks. The development of an interactive program control scheme would be facilitated by previous simplification of input requirements for droplet spectra and stand descriptions, and the development of a summary display module. The summary display module cannot operate unless the program is altered to perform deposition calculations simultaneously for all heights. The development of measures of effectiveness for herbicides and insecticides also depends on the availability of data for the complete height profile through the canopy, as well as deposition calculations by tree type. An improved fitting of impaction and probability of penetration coefficients should be preceded by any changes in the impaction model, and corrections for varying wind speeds. The sensitivity analysis, of course, should not be performed until the basic model alterations for this mod have been accomplished, and this analysis will be facilitated by upgraded control structures. The preparation of the necessary documentation will complete MOD 1.

The further development of the system from MOD 1 to MOD 2 is depicted in Figure V-2. The order of the tasks recommended during this phase of development is in many cases not critical, but a few precedence relationships must be maintained. A method for dosage (concentration times time) prediction below the canopy

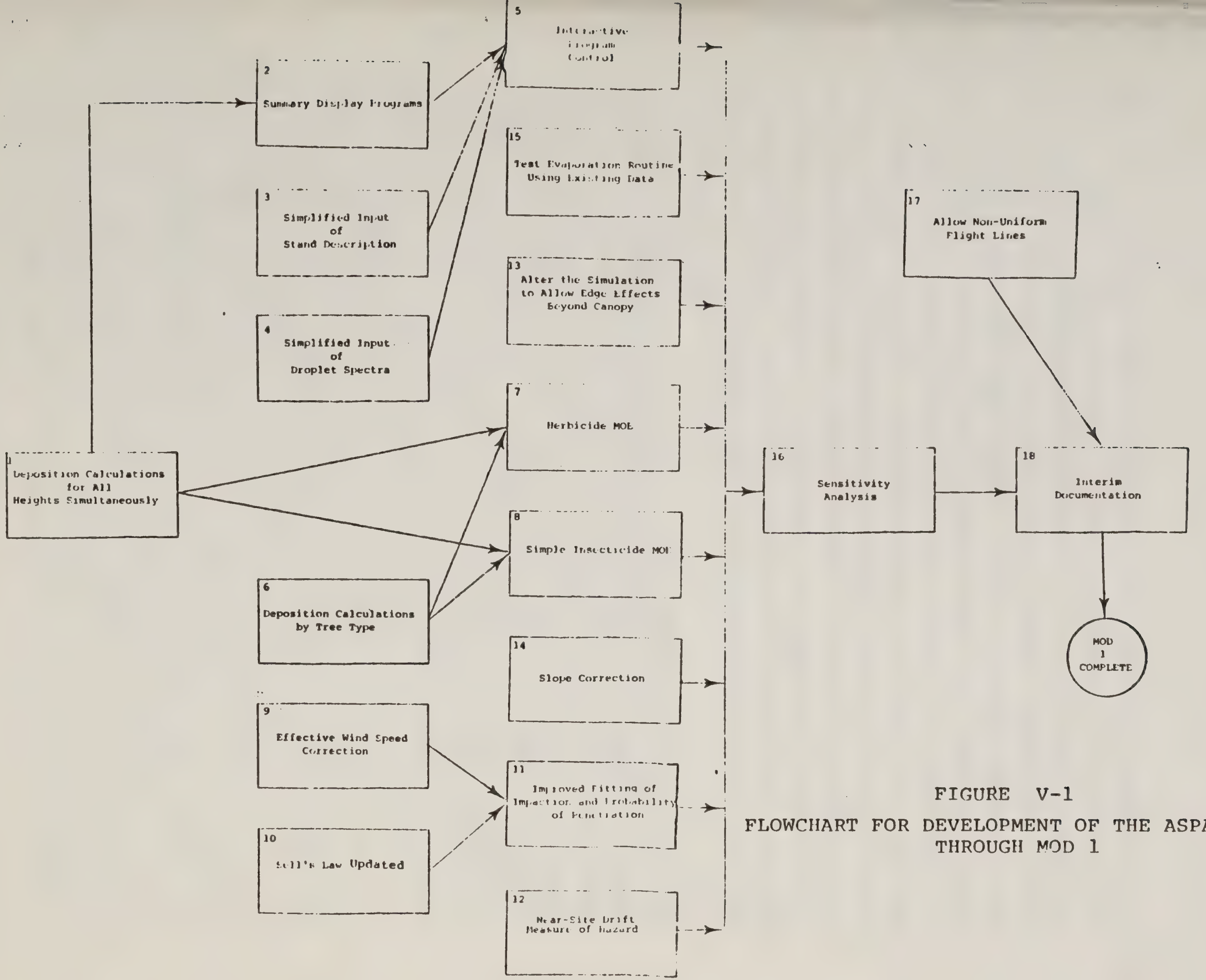


FIGURE V-1

FLOWCHART FOR DEVELOPMENT OF THE ASPAS THROUGH MOD 1

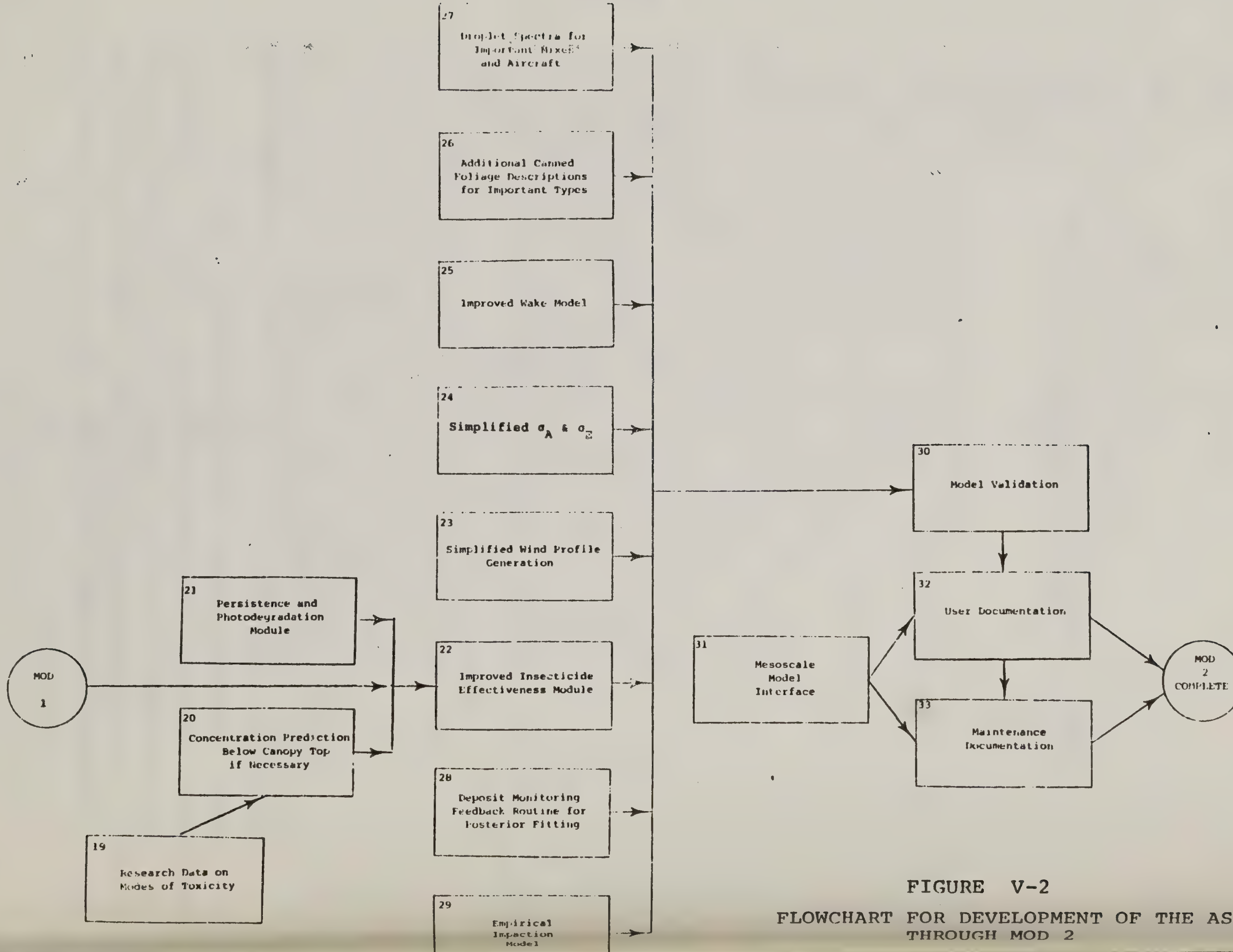


FIGURE V-2

FLOWCHART FOR DEVELOPMENT OF THE ASPAS THROUGH MOD 2

should not be developed unless the toxicological research indicates that it is necessary (it will be a very difficult item to address if it should prove necessary). If the dosage prediction should be developed, it will have to precede improvement of the insecticide effectiveness module. The insecticide effectiveness module will also make use of persistence and photodegradation calculations. Model validation should await the model improvements of MOD 2, and the documentation produced for this mod should reflect the validation analysis. Validation is an important requirement at this stage because it marks the completion of improvements designed to increase the accuracy of the basic simulation model. Improvement of the wake model is important in this regard. The completion of documentation will finish the development of MOD 2.

The improvements to the system recommended for the next phase of development are aimed primarily at increasing its scope of applicability and creating mechanisms for bringing about better information transfer. The tasks recommended for bringing the system from MOD 2 to MOD 3 are shown in Figure V-3. The development of synopsis versions will depend on an adequate representation of evaporation. Investigation of the effects of spray adjuvants can also build on the evaporation data. Parameterization of the monte-carlo simulation may be called for if the prospective use volume is great enough, but at this point it seems that it will be unnecessary. To the extent that synopsis versions are used instead of the main system, such streamlining of computations will be obviated. Synopsis versions, in all cases, should not be developed until validation of the model under relevant circumstances. Adaptation of a conventional agricultural aerial spray deposition model to account for areas with low-lying vegetation is at this point expected to be a valuable improvement. However, this hinges on the supposition of widespread herbicide use. Development of the proper documentation will again mark the completion of the mod. Development

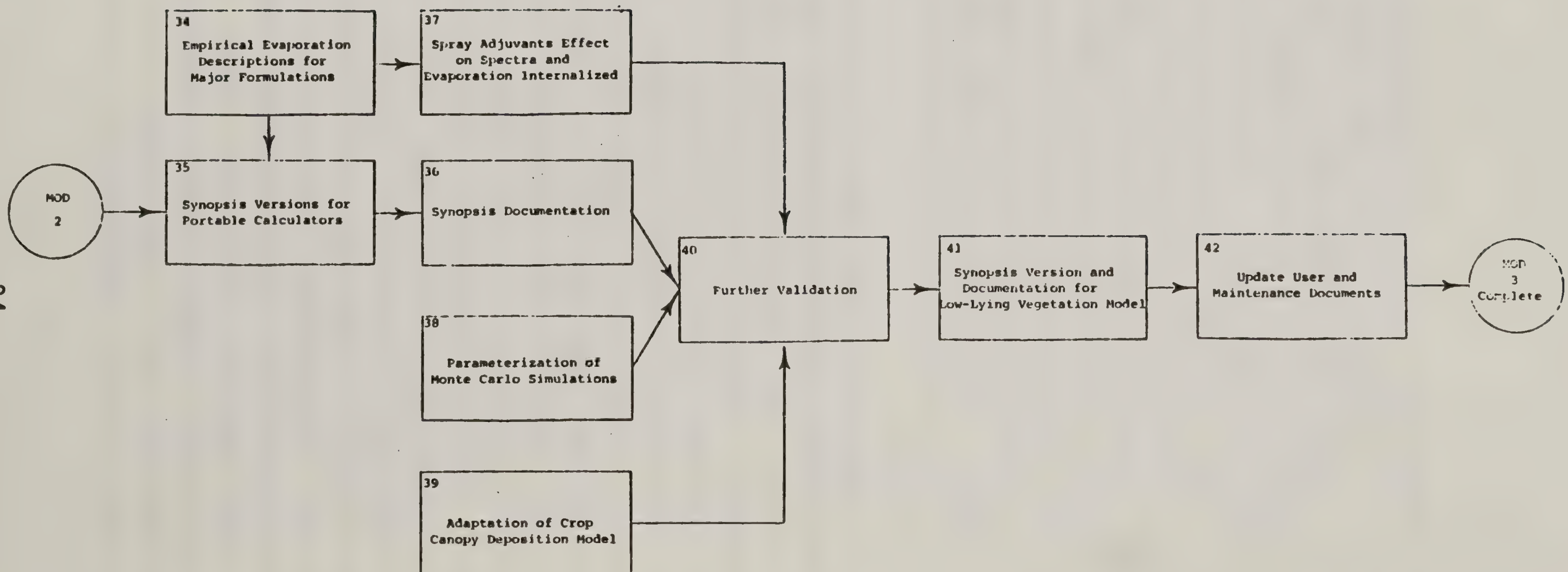


FIGURE V-3

FLOWCHART FOR DEVELOPMENT OF THE ASPAS
FROM MOD 2 THROUGH MOD 3

beyond this phase cannot be recommended at this time, but the need and prospects for system improvement should be reassessed at the completion of MOD 3.

All of the tasks recommended for the development of the ASPAS system through MODs 1, 2, and 3 are diagrammed in the PERT (Projection Evaluation and Review Technique) chart shown in Figure V-4. Each of the tasks (or activities, in standard PERT terminology) is represented by an arrow. The tasks are identified by numbers which refer to Table V-1. The nodes, indicated by letters in circles, simply represent points at which the preceding tasks have all been completed. Arrows made up of dashed lines are "dummy" activities, which do not represent tasks to be completed but which simply indicate precedence relationships. All activities coming into a node must be completed before any activity leaving that node is begun. Estimated times required for completion and estimated manpower requirements are also listed in Table V-1. An analysis of the PERT network on the basis of these times indicates that the shortest total time in which the ASPAS could be completed through MOD 3 would be about 60 months from the start of work. This represents the time required to complete all activities along the "critical path". These activities indicated by a "C" in the third column of Table V-1, are those upon which the speed of development depends. The other tasks in the network, indicated by "N" in Table V-1, are non-critical in the sense that their scheduling involves "slack time", which represents the magnitude of delays which could be tolerated without affecting the earliest possible completion of the project. The 60 month estimate for earliest possible completion rests on all of the assumptions about precedence relationships and time requirements for the activities, and does not take into account any restrictions on manpower on budget.

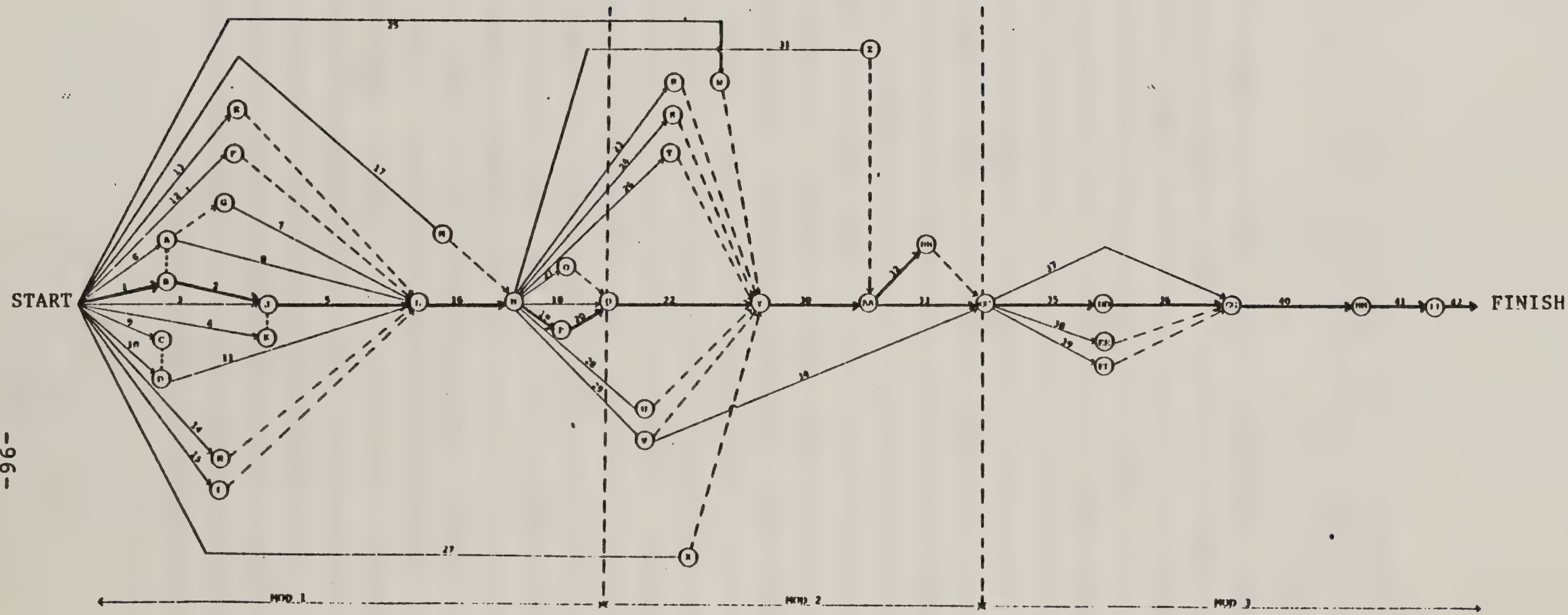


FIGURE V-4

PERT CHART OF TASKS FOR ASPAS
DEVELOPMENT THROUGH MOD 3

TABLE V-1

TASKS IDENTIFIED BY NUMBER, WITH ESTIMATED TIME AND MAN-POWER REQUIREMENTS

TASK	DESCRIPTION	CRITICAL(C) OR NON-CRITICAL(N)	ESTIMATED TIME REQUIREMENT	ESTIMATED MANPOWER OR COST
1	DEPOSITION CALCULATIONS FOR ALL HEIGHTS IN CANOPY	C	3 WEEKS	3 MAN-WEEKS
2	SUMMARY DISPLAY PROGRAMS	C	2 MONTHS	2 MAN-MONTHS
3	SIMPLIFIED INPUT OF STAND DESCRIPTION	N	4 WEEKS	4 MAN-WEEKS
4	SIMPLIFIED INPUT OF DROPLET SPECTRA	N	4 WEEKS	4 MAN-WEEKS
5	INTERACTIVE PROGRAM CONTROL	N	4 MONTHS	4 MAN-MONTHS
6	DEPOSITION CALCULATIONS BY TREE TYPE	C	6 WEEKS	6 MAN-WEEKS
7	DEVELOPMENT OF HERBICIDE MOE	N	3 MONTHS	4 MAN-MONTHS
8	SIMPLE INSECTICIDE MOE	N	3 MONTHS	3 MAN-MONTHS
9	EFFECTIVE WIND SPEED CORRECTION	N	5 WEEKS	6 MAN-WEEKS
10	SELL'S LAW UPGRADED	N	6 WEEKS	7 MAN-WEEKS
11	IMPROVED FITTING OF IMPACTION AND PROBABILTY OF PENETRATION	N	1 WEEK	1 MAN-WEEK
12	NEAR-SITE DRIFT MEASURE OF HAZARD	N	3 WEEKS	3 MAN-WEEKS
13	ALLOW EDGE EFFECTS OF CANOPY	N	6 WEEK	6 MAN-WEEK
14	SLOPE CORRECTION	N	1 WEEK	1 MAN-WEEK
15	TEST EVAPORATION ROUTINE USING EXISTING DATA	N	1 1/2 WEEK	1 1/2 MAN-WEEKS
16	SENSITIVITY ANALYSIS	C	2 MONTHS	2 MAN-MONTHS
17	ALLOW NON-UNIFORM HEIGHT FLIGHT LINES	N	2 WEEK	2 MAN-WEEK
18	INTERIM DOCUMENTATION	N	3 MONTHS	3 MAN-MONTHS
19	RESEARCH DATA ON MODES OF TOXICITY	C	12 MONTHS	18 MAN-MONTHS
20	CONCENTRATION PREDICTION BELOW THE CANOPY	C	---------	----------*
21	PERSISTENCE AND PHOTODEGRADATION MODULE	N	4 WEEKS	5 MAN-WEEKS
22	IMPROVED INSECTICIDE EFFECTIVENESS MODULE	C	12 MONTHS	18 MAN-MONTHS
23	SIMPLIFIED WIND PROFILE GENERATION	N	6 WEEKS	9 MAN-WEEKS
24	SIMPLIFIED σ_A AND σ_E GENERATION	N	4 WEEKS	5 MAN-WEEKS
25	IMPROVED WAKE MODEL	N	5 MONTHS	8 MAN-MONTHS
26	ADDITIONAL CANNED FOLIAGE DESCRIPTIONS	N	9 MONTHS	15 MAN-MONTHS
27	DROPLET SPECTRA FOR IMPORTANT MIXES AND AIRCRAFT	N	12 MONTHS	18 MAN-MONTHS
28	DEPOSIT MONITORING FEEDBACK ROUTINE	N	3 WEEKS	3 MAN-WEEKS
29	EMPIRICAL IMPACTION MODEL	N	12 MONTHS	18 MAN-MONTHS
30	MODEL VALIDATION	C	6 MONTHS	$300
31	MESOSCALE MODEL INTERFACE	N	4 MONTHS	6 MAN-MONTHS
32	USER DOCUMENTATION	C	4 MONTHS	3 MAN-MONTHS
33	MAINTENANCE DOCUMENTATION	C	4 MONTHS	3 MAN-MONTHS
34	EMPIRICAL EVAPORATION DESCRIPTIONS FOR MAJOR FORMULATIONS	N	8 MONTHS	12 MAN-MONTHS
35	SYNOPSIS VERSIONS FOR PORTABLE CALCULATORS	C	8 MONTHS	12 MAN-MONTHS
36	SYNOPSIS DOCUMENTATION	C	2 MONTHS	2 MAN-MONTHS
37	DETERMINATION AND INTERNALIZATION OF ADJUVANT EFFECTS ON SPECTRA AND EVAPORATION	N	6 MONTHS	10 MAN-MONTHS
38	PARAMETERIZATION OF MONTE CARLO SIMULATION	N	---------	----------*
39	ADAPTATION OF A CROP CANOPY DEPOSITION MODEL	N	6 MONTHS	6 MAN-MONTHS
40	FURTHER VALIDATION	C	2 MONTHS	$100
41	SYNOPSIS VERSION AND DOCUMENTATION FOR LOW-LYING VEGETATION MODEL	C	3 MONTHS	4 MAN-MONTHS
42	UPDATE USER AND MAINTENANCE DOCUMENTS	C	2 MONTHS	2 MAN-MONTHS

TOTAL: 15.7 MAN-YEARS

* MANPOWER HAS NOT BEEN ESTIMATED FOR THESE TASKS BECAUSE THEY WILL MOST LIKELY NOT BE NECESSARY

The total man-power estimate is 15.7 man-years, including work by all supporting contributors, as well as the Forest Service. The personnel required will be diverse, since they will be involved in laboratory studies, model design, computer programming, field studies and validation.

The actual scheduling of tasks can be done somewhat flexibly, even within the minimum time constraint. One of the possible schedules is shown in Figure V-5 as a gantt chart. It can be seen that many tasks of short duration have been scheduled for the initial phase of development, in order to increase the utility of the system as soon as possible. The manpower requirements are relatively high in year 3, and low in year 5. If it is necessary to distribute the work more uniformly, then the validation studies of year 3 could be delayed somewhat. This would produce a much more even schedule, but would necessarily also delay completion of MOD 2.

It should be noted that the tasks discussed above would not necessarily all be new undertakings for the Forest Service. Some of the types of work suggested in the plan are already programmed by either FIDR or FPM. The emphasis of the existing research would have to change somewhat to support the plan. It should also be emphasized that the research called for by the development plan is of interest to parties other than the Forest Service. As pointed out in a previous section, similar work is being sponsored by APHIS, the branches of the U.S. military, and some Canadian organizations. Every effort should be made to share development costs where possible, and to avoid duplication.

The manpower estimates given in this section should certainly not be considered to be precise estimates. The exact requirements will depend on a number of factors, including the availability of the preferred personnel and equipment to do the

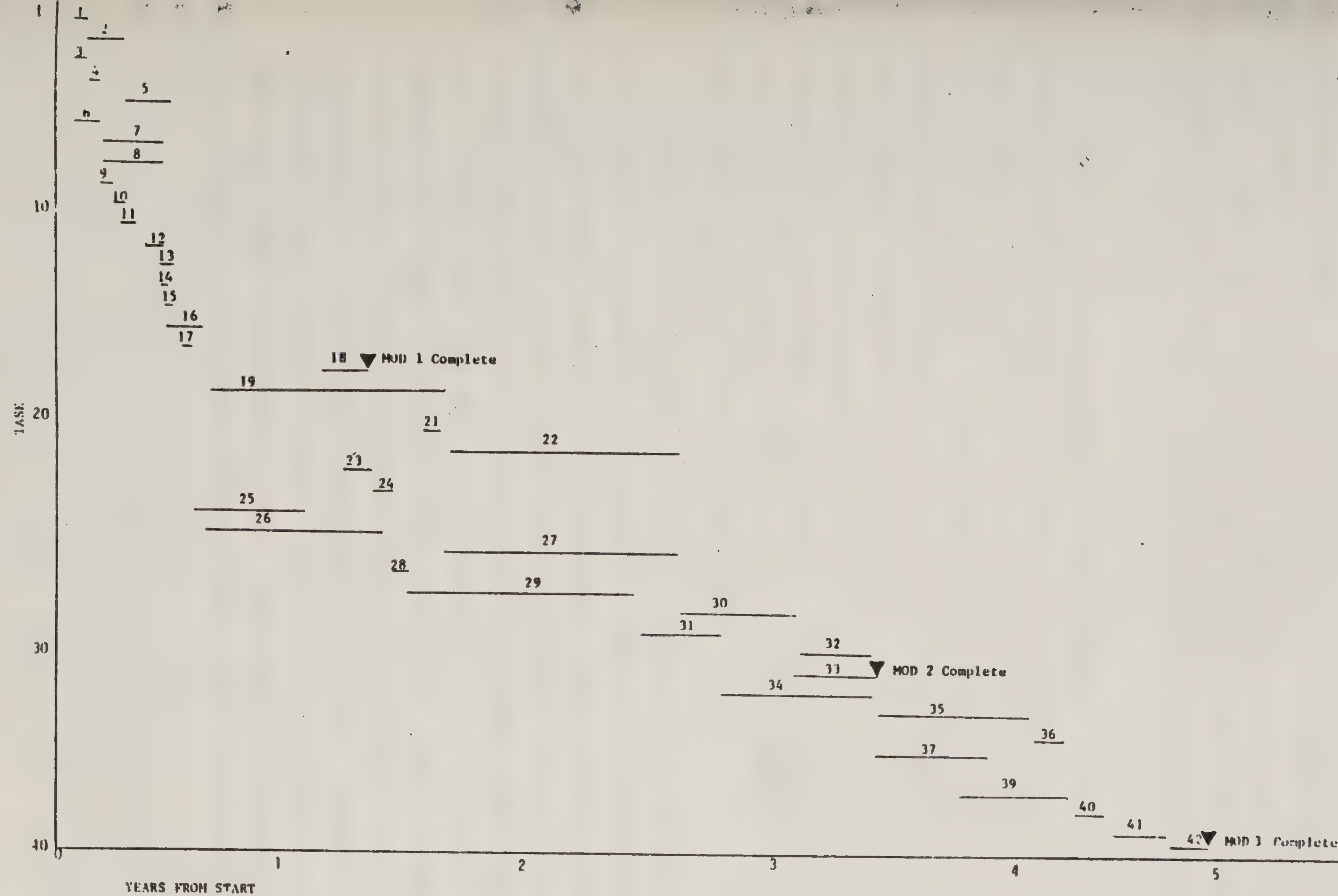


FIGURE V-5

ONE FEASIBLE SCHEDULING OF TASKS FOR DEVELOPMENT OF ASPAS THROUGH MOD 3

job. Both the cost and the time required by some tasks are expected to be minimized to the extent that similar tasks can be grouped into packages. This is especially true of the smaller tasks, some of which would be very inefficiently undertaken singly.

SECTION VI
CONCLUSION

The plan presented in this report for development of an Aerial Spray Planning and Analysis System has been designed for cost-effectiveness in several aspects. Existing models and data will be exploited where possible and appropriate. The FSCBG model which will form the basis of the system is the result of development efforts by both the U.S. military and the Forest Service. Future developments can make use of existing wake and mesoscale meteorological models. Opportunities also exist for sharing the burdens of both model development and supporting research among interested organizations.

It is widely recognized by experts in the field that there is a genuine need for a stronger information base and for methods of analyzing forest and rangeland pesticide applications. A recent report by the Comptroller General points out the need for better data for making vegetation management decisions (Report by the Comptroller of the U.S., April 17, 1981), and insect control operations face similar needs. As has been pointed out in the introduction, many of these needs were identified by the Aerial Application Technology Workgroup in their problem analysis of "Forest and Range Aerial Pesticide Application Technology". Specific points raised by that committee which have been addressed by the plan for ASPAS development include the following:

- "The performance of individual components and total aircraft spray delivery systems has not been adequately quantified to permit development and selection of equipment and prediction of spray delivery in conjunction with a variety of spray materials, meteorological conditions, and terrain."

The ASPAS will provide a system for analysis of the behavior of spray delivery systems and the impact of component changes.

- A framework does not exist "to organize information and to develop a strategy for planning and conducting aerial spray projects."

The ASPAS will provide a system for organization of relevant knowledge, and determination of consistent and objective strategies. As part of this process, the ASPAS will incorporate expert judgement to some extent especially in its early stages. These first MODs will enable the specialist to find an appropriate prescription for an aerial spray project, but later MOD's will directly produce prescriptions for less specialized personnel.

- Advances in aerial application technology are hindered by the lack of information on the relationship and interaction of the pesticide, environment, weather, and host to the target pest. Field experiments, pilot projects, and operational projects have had highly variable results, expecially with biological agents.

The ASPAS will provide a system for explicit representation of interactions between aspects of spray delivery system engineering, meteorology, the site, and the target pest. The impact of these factors will be meaningfully related to appropriate measures of effectiveness.

- "Accurate models of spray behavior require input on wind velocities and mixing efficiency that are difficult to measure on-site".

The ASPAS will incorporate models which relate wind velocity profiles within and above forest stands to more easily observable quantities describing stand characteristics and meteorology.

- "Current weather criteria used on operational spray operations do not avoid long - and medium - range drift hazard."

The ASPAS itself need not incorporate models of drift on this scale, but instead existing mesoscale models can be utilized by developing an appropriate interface with the ASPAS. This will allow a more accurate appraisal of drift hazard than has been seen in the past. A basic problem here has been that spray drift is not measurable with most of the same equipment and methods used to evaluate target area spray coverage (MEDC, 1977). Analytical methods then are more important.

- "Quantitative data on the physical behavior of spray droplets are needed from the time the spray leaves the aircraft spray system to the time it comes to rest or is changed from a liquid to a gaseous state. A systematic engineering approach using computer modeling techniques is needed to make full use of all information and data on spray behavior. The overall model would balance and weigh each input and provide the planner with options and alternatives for decisions. Output could be used during all project phases, including planning, spraying, and evaluation".

The ASPAS development will coordinate the relevant data gathering and spray behavior modeling, implementing a systematic engineering approach.

- "Pesticide drift into sensitive non-target areas has the potential of causing environment contamination, public health hazards, adverse publicity, and increased project costs from claims and legal actions."

The ASPAS will provide a tool for drift management, supplementing the technical skills and experience of project personnel. It will enable application planners to maintain consistent and objective standards for offsite drift control. Monitoring data can be better utilized. Analysis produced by the system would serve as the best available evidence in legal proceedings, but more importantly such litigation could be more easily prevented.

- "Existing technology is not being used to the extent possible to improve the planning and conducting of operational spray projects."

The ASPAS development plan provides means for effective transfer to field use of the best available information and analytical methodology. This information will be in forms amenable to project planning, operational guidance, and project evaluation. The system will also serve as a valuable resource for training of aerial application personnel. It will eliminate the need for much trial and error learning that has occurred in the past on operational projects.

The system of models comprising the ASPAS should not be expected to achieve complete accuracy. Among the many physical and chemical factors which must be addressed by the system, air flow patterns and turbulence within the forest canopy are particularly difficult to deal with. Improvement in the state-of-the-art may come in the future, but the participants of a 1978 Ottawa workshop on research needs in forest meteorology generally concluded that "turbulence phenomena are among the most complex and intractable physical process known to contemporary science. Consequently, advances in the problem of turbulence in forests may come slowly" (Hutchison, 1979). In the meantime, we should make use of the best practicable models while realizing their limitations. It should also be realized that reaching the greatest possible accuracy and precision is not in itself a valid objective. Rather, we should try to find the most appropriate match between attainable techniques and knowledge and the needs of the users. The APSAS will be an appropriate receptor for new data and component models as they become available, since it will allow new information to be systematically integrated, showing the relationship to other components of the system. The value of the new information could then be properly assessed in terms of overall measures of effectiveness and usefulness of the improvement to the end user.

The Forest Service should not commit itself to an ultimate design for the system, but the specific needs for the system should be reassesed in the future, especially at the completion of MOD 3. However, the recommended evolutionary scheme will:

- produce a very useful system in a short time,
- maintain modularity and flexibility of the components,
- enable the system to be used over the whole range of major aerial pesticide application situations, including insecticides and herbicides on common forest types,
- produce a very usable system in terms of data input, program control, and handling and intepretation of output and,
- create an Aerial Spray Planning and Analysis System designed to produce information of a kind and format which can easily be transferred to field use.

The details of the proposed plan are quite flexible in many respects. The Forest Service will have to consider budgeting limitations and specific opportunities for collaboration with other agencies before finalizing plans for development of ASPAS. These factors will ultimately control the rate of development and the choice of particular tasks undertaken.

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APPENDIX A

A SYSTEMS ANALYTIC FRAMEWORK FOR PLANNING AND DECISION-MAKING IN FOREST MANAGEMENT AERIAL APPLICATIONS OF PESTICIDES AND HERBICIDES

INTRODUCTION

The objective of this analysis is the development of a systematic understanding of forest pest suppression management with emphasis on the role of planning and decision-making in aerial pesticide and herbicide application.

To achieve this objective we develop a systems analytic framework, identifying actors and organizations, functions and responsibilities, and activities, as well as the interfaces and interrelationships among these entities.

In this framework we focus on the roles of models and data bases, identifying where they are currently employed and asking where improved models might bring real gains in suppression management cost/effectiveness. An essential feature of our approach is the identification of subjective, experiential models currently employed in forest management. Such models are usually thought of only in terms of "expert judgment" or "experience", not as models. Yet the "expert" takes some sort of information (input data) and processes it in some way to obtain estimates or predictions (output data) for variables of interest. But this is just what a quantitative, computational model does. New quantitative models may therefore not accomplish new function so much as accomplish existing functions (hopefully!) better.

In the next section we present an overall systems view of forest pest suppression management. This is followed by a section focusing on the subsystem for aerial applications of pesticides. Although the focus of these sections is pest management, the essential elements are similar in planning and decision-making for herbicide application.

A GENERIC SYSTEMS VIEW OF FOREST PEST SUPPRESSION MANAGEMENT

Description of the Suppression Management Sequence

The only large-scale suppression technique currently available to the pest manager is the spraying of insecticides or herbicides. Other suppression techniques, such as painting egg masses, trapping larvae, or conducting controlled burns are only suitable for very small scale operations.

Figure A-1 shows a generic diagram of a spray suppression operation. This diagram subsumes spray operations conducted by state, federal, and local agencies. The exact activities performed, and their timing, vary somewhat among agencies. Let us briefly discuss these activities, keying our comments to the numbering in the figure. We are going to be particularly interested in the roles of models and data bases -- both quantitative and experiential -- in suppression management, and therefore underline those activities where models and data bases are employed. The bulk of these involves implicit exercise of experiential models. Although this is just another way of saying "employment of expert judgment", it emphasizes the fact that quantitative models (nomograms, computer programs, technical data) could potentially be employed in the same role, if developed and validated.

Sequence Description. (1) The pest manager must often provide budget estimates for pest suppression projects a year or more in advance. For this he must make long-range forecasts of insect outbreaks, or undesirable understory growth, implicitly employing some sort of prediction model, if only the subjective model residing in his mind. (2) The appropriate funding agencies initiate the budget process. (3) During larval development the pest manager detects threatening populations through means such as aerial sketch-mapping of defoliation, and through reports of sighted pest activity by citizens and the pest management staff

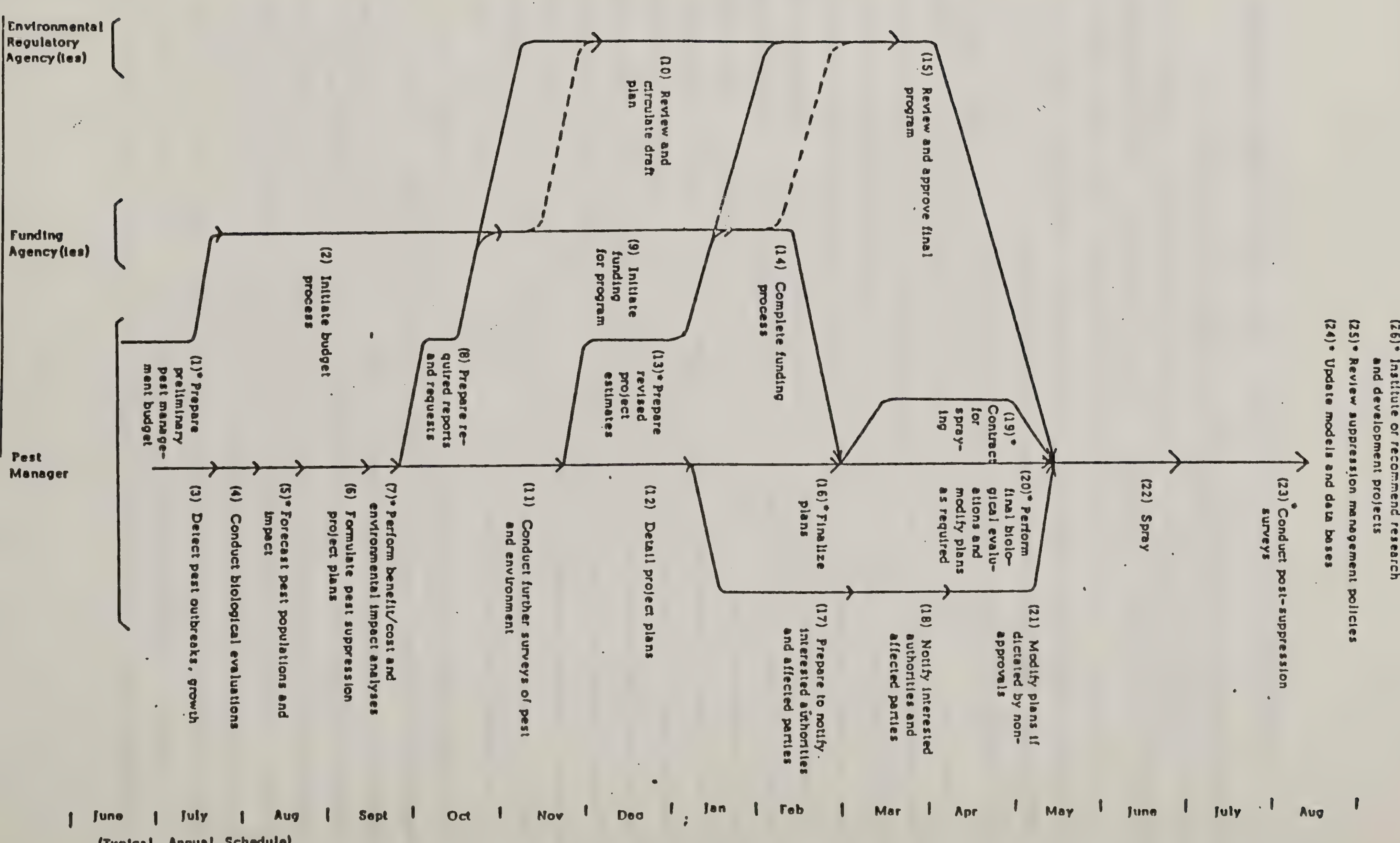


FIGURE A-1

A GENERIC PEST SUPPRESSION PROGRAM

*Activities which implicitly require models and archival data.

in the field. The forest manager may similarly determine need for understory vegetation control. (4) Biological evaluations are then conducted by ground survey if the causative agent or level of threat is in question. (5) The pest manager then makes, using subjective or objective models, preliminary forecasts of pest populations for next cycle in the areas of concern, and (6) uses these forecasts together with decision rules to recommend which areas should be sprayed the coming year. The decision rules are based on implicit or explicit models and data on socioeconomic and environmental impacts. (7) He then performs more detailed benefit/cost and environmental impact analyses (using available cost/benefit models and data) required to (8) prepare requests for funding (if line funds are not available) and environmental and regulatory agency approval. These requests must usually be submitted many months in advance of planned spraying in order to allow time for the review processes to be completed. In the case of cooperative federal/state funding, the federal agency (U.S. Forest Service -- State and Private Forestry) prepares the required environmental impact statement, based on data supplied rather informally by the states. (9) The funding agency, and (10) environmental regulatory agency then initiate their review processes of the programs.

(11) Later in the planning cycle (e.g. in the fall and winter) the pest manager may conduct further biological surveys, e.g., egg mass counts in the areas scheduled for treatment, in order to sharpen his forecasts of upcoming pest populations. (12) He uses these new estimates to begin detailing the suppression project plan (identifying spray blocks, etc.). Using an archival data base for spray rates, pesticide/herbicide effectiveness, costs, and environmental impact, he (13) prepares revised requests for (14) funding, and (15) regulatory approval.

(16) The pest manager next finalizes his spray plans, specifying pesticide/herbicide formulation, spray equipment, spray

schedule, and so forth. For this he employs an archival data base, giving equipment capacities, average weather conditions, spray rates, and so forth. (17) He prepares to notify interested authorities and affected parties. He identifies homeowners, blueberry farms, organic farms, beekeepers, and other affected parties in or near the spray blocks by working from tax rolls, agricultural registers, etc. (18) He then sends out notices of intention to spray, and permission forms, if applicable.

(19) Meanwhile he has begun the process of contracting for spraying services, although technically he may be unable to sign a contract until final funding is approved. In specifying the services and evaluating bids, he implicitly employs models and data such as miss and skip rates as a function of aircraft type and speed, price paid, and even specific contractor selected.

In the month or two preceding the spray operation the pest manager may eliminate or, rarely, add spray blocks from his plan based on (20) final biological evaluation (e.g., by examining or testing egg masses to estimate hatch rate), or (21) nonapproval by affected parties (if they have veto authority). Once this final scale-down is completed, and required approval from regulatory agencies is received (or at least nonapproval is not received), then (22) the spray operation can commence. This, of course, involves assembling and organizing personnel, waiting for good weather, making motel and airport arrangements, etc. It also will involve immediate respraying where coverage is deemed deficient, and later respraying where ground evaluation shows inadequate effectiveness.

(23) Later in the cycle, post-suppression surveys may be conducted to ascertain the effectiveness of the spray operation and to determine if further spraying is required the next year. Note that such post-suppression surveying overlaps, and in fact forms a part of, the initial planning steps (3)-(6) for the next

suppression program. Also note that the evaluation of treatment effectiveness using this post-suppression data may involve the exercise of subjective or objective models of pest population dynamics in order to appreciate what would have occurred without treatment.

This completes the basic yearly cycle. The suppression manager then reviews the past year's program. He (24) implicitly or explicitly revises or updates his models and data bases in light of new data. He (25) reviews suppression management policies and procedures. Finally, he initiates or recommends specific research on pest behavior or suppression management tools and techniques.

Classification of Suppression Management Activities

It is useful to group suppression management activities into five categories: (1) Policy Formulation and Update, (2) Routine Planning and Forecasting, (3) Execution, (4) Evaluation, and (5) Research.[1]

Policy Formulation and Update. This category of suppression management covers such things as determining treatment thresholds, dictating pesticide selection and application equipment, and setting weather criteria for halting spray operations.

There are two levels of sophistication which can be involved in these activities. At the highest level the structure of the policy is reviewed, while at the lower level the parameters of

[1] It is interesting to note that this identification is almost identical to that presented in: Barry, John W., "Aerial Application Technology," in Brookes, Martha H., et. al., ed., The Douglas-Fir Tussock Moth: A Synthesis, USDA, Forest Service, Science and Education Admin., Technical Bulletin 1585, 1978, pg. 159. In that article the identified activities in forest spray operations are: (1) Requirements Analysis, (2) Development of Operations Plan, (3) Spray Operations, (4) Data Analysis, and (5) Refinement of Spray Techniques.

the policy are simply adjusted. For instance, at the higher level the suppression manager might decide to explicitly take account of wilt disease in deciding on gypsy moth treatment. He would then make the treatment threshold egg mass density a function of some rigorously measured wilt disease index, in addition to other parameters already considered. In subsequent years he would operate at the lower level of sophistication in updating the policy, simply adjusting the coefficient of wilt disease contribution in the egg mass density threshold equation.

Routine Planning and Forecasting. In this category of activities the suppression manager is concerned with predicting the course of pest activity with and without treatment, and with planning those treatments decided upon.

The actual type of forecasting undertaken depends on the structure of the treatment policy. If the policy is formulated in terms of treatment thresholds for a given parameter, this is equivalent to predicting acceptable pest populations if the parameter falls below the threshold and unacceptable populations if it falls above; thus, no explicit forecast of pest populations is required. If, on the other hand, the treatment policy is formulated directly in terms of pest activity or impact (e.g. by specifying a threshold defoliation) then that activity or impact must be predicted.

Execution. Once the suppression manager has formulated his plans he must then carry them out. This execution involves soliciting bids and awarding contracts for spray material and services, directing and supervising the spray operation, notifying potentially affected citizens, etc.

Evaluation. The suppression manager, preparatory to policy update and reformulation, should undertake an evaluation of the past year's activities. This should include a general review of overall suppression management strategies, tactics, and sequences, in addition to the explicit evaluation of treatments, forecasting models, and other suppression management tools.

Research. This process consists of identifying problems to be solved, problems for research, or proposing new pest management techniques and equipment. The pollen excluder used in New Jersey to prevent bee mortality from carbaryl spray was developed in response to a problem identified in routine suppression operations. Inspection of defoliation maps compiled in routine operations and overlaid onto topographic maps suggested that gypsy moth larvae were being blown particularly far from ridges, leading to proposals to selectively treat ridges in order to reduce the rate of spread of the gypsy moth. Experience with gypsy moth outbreaks led to the theory, yet unproven, that outbreaks begin in certain highly susceptible forest stands and then propogate outward; if this theory were to be verified, a completely new suppression system might become feasible, in which focal areas would be carefully monitored and suppressed at the first indication of outbreak condition.

Classification of Suppression Management Assets

The state or federal pest suppression manager has three categories of assets with which to work:

(1) Technology includes pesticides/herbicides and formulations, treatment equipment and techniques, forest environment monitoring equipment and techniques, and pest population monitoring equipment and techniques.

(2) Models and Data Bases include the experiential formulations residing in the minds of the suppression manager and of his staff, as well as objective computational algorithms or data compilations; these models and data bases are employed by the suppression manager in selecting and applying the available technology as efficiently as possible. Such models and data bases provide information such as: (1) forecasts of defoliation based on egg mass counts and stand composition; (2) forecasts of defoliation based on previous year defoliation; (3) estimates of

drift from spray areas as a function of wind, spray equipment, and delivery parameters; (4) estimates of miss and skip rates as a function of aircraft type, altitude, and chase plane employment.

(3) Money and Manpower refer, obviously, to the suppression manager's budget and staff. The budget determines how much suppression the manager can undertake. Staff numbers and quality, in terms of experience and education, dictate how well the suppression technology can be employed.

The Suppression Manager's Models and Data Bases

We have argued that the suppression manager employs models and data bases, at least implicitly, in all phases of his work except possibly Execution. To help fix this concept, let us list a number of such models and data bases:

- Pest population outbreak distribution as a function of previous year population surveys -- used in routine planning to allocate current year biosurvey activity.

- Defoliation as a function of egg mass counts and other biological data -- used in forecasting defoliation or in formulating or updating treatment policy.

- Accuracy of egg mass survey as a function of egg mass density, time of survey, and method -- used in formulating survey policy, or in assigning level of uncertainty to predictions of gypsy moth activity.

- Number of persons and organizations telephoning or writing state agencies or congressional representatives to request spray action, as a function of pest activity and uses of infested forest -- used in treatment policy formulation and pesticide selection.

- Strength of opposition to spray program by environmentalist groups, as function of proposed area of application and

pesticide selection -- used in treatment policy formulation and pesticide selection.

- Expected collapse of treatment block boundary (expressed as distance into treatment block such that defoliation exceeds 30%, say) as function of pesticide and median larval instar at application -- used to adjust policy on treatment block buffer zone.
- Tree mortality as a function of frequency and severity of defoliation -- used in formulating or adjusting treatment policy.
- Miss and skip rate in aerial spray as a function of aircraft type, treatment block size, wind, numbers and type of marking balloons, use of chase plane, etc., -- used in formulating treatment plans.
- Number of acres sprayed per hour, as function of aircraft type, average block size, average distance between blocks, average distance to nearest airfield or landing/loading area -- used in determining number of aircraft required.
- Pesticide/herbicide drift and deposition as function of wind direction and speed, thermal gradient, pesticide formulation, source droplet distribution, aircraft speed and height, and canopy density -- used to help select equipment and materials, to develop general guidelines for aerial spray procedures (constraints, recommended delivery parameters, etc.), to plan for specific projects, and to prepare environmental impact statements.

The list of models and data bases can be extended to cover virtually every facet of pest management. It must be remembered that the bulk of these models are experiential and subjective, and constitute the real expertise of the suppression manager and his staff. But by treating this expertise as a collection of models, we can develop a good appreciation of the limitations and potential payoffs of improved models and data bases.

The Benefits of Improved Models and Data Bases

Feedback and research can lead to improvements in the suppression manager's models and data bases. What will this buy in real terms? This question proves to be exceedingly complex. We will sketch the outlines of an answer in the following paragraphs, looking at each category of suppression management activity.

Policy Formulation and Update. The suppression manager has formulated various policies to make automatic many of his routine decisions. He may not, for instance, decide how extensive an egg mass survey to do on a plot-by-plot basis. Rather, he might set a policy of investing the same amount of time for each plot. The level he selects will be based on a complex, almost certainly subjective model yielding some measure of overall suppression management efficiency as a function of survey accuracy, which is in turn a function of survey investment. As this model is adjusted through feedback to better fit real experience, the policy recommended by the model will be improved.

The suppression manager, may, through feedback or research, build a more sophisticated model of the contribution of survey investment to overall suppression management efficiency. He might add a land use factor. He might even add parameters reflecting a sequential sampling survey scheme. From this more sophisticated model would emerge more sophisticated policies, e.g., "Perform a count of visible gypsy moth egg masses on a randomly selected 1/40th acre plot; if the count yields less than 50 or more than 500 egg masses per acre in a recreation area, stop the survey; otherwise survey two more 1/40th acre plots and stop."

We thus see two types of model improvement, bringing two types of policy update or reformulation:

- Model adjustment brings policy adjustments;
- Model enrichment brings policy enrichment.

Either type of policy improvement can bring real gain to suppression management efficiency.

To focus these important concepts in the area of immediate interest, consider another example. It has been pointed out that many working forest biologists and pest managers are employing simplistic and outdated subjective, experiential models of spray cloud behavior, developed in the 1950's when "application rates were one gallon per acre, desirable spray deposit was above 100 micrometers, and the aircraft flew at 100 mph."[2] Simple policies as to aircraft height, swath width, and wind velocity constraints were derived from these models, but frequently produced unsatisfactory spray coverage and drift control when used for aircraft flying 200 mph, spraying droplets less than 50 micrometers in diameter at application rates of 1/4 gallon per acre. Such discrepancies undoubtedly have led fieldmen to adjust their experiential models, perhaps by (essentially) raising some coefficient of wind drift for the smaller droplet spray cloud. This in turn results in such policy adjustments as the tightening of wind constraints for the finer sprays.

The pest manager is, we imagine, further finding it necessary to enrich his subjective model by taking explicit account of: spray particle size distribution; temperature gradients; aircraft type, size and speed; and other new factors. This would lead to enriched policies involving these new factors in addition to those already considered.

[2] Ekblad, Robert, et. al., Forest and Range Aerial Pesticide Application Technology - A Problem Analysis, Forest Service Missoula Equipment Development Center, Missoula, Montana, July 1979, page 81.

Such model improvement and enrichment has been taken beyond the realm of subjective models and into the realm of quantitative computer models with development of models such as the Forest Service Cramer/Barry/Grim (FSCBG) Computer Program.

Routine Planning and Forecasting. The pest manager must make numerous forecasts to aid his planning and decision-making. For instance, he may want to spray gypsy moth treatment blocks after 90% of the viable eggs have hatched, but not before 50% of the larvae reach the third instar. He then needs a model to forecast the date of 90% hatch. The model he employs may be at any of many levels of sophistication. It may use degree-days since the beginning of winter as the only input parameter. Or it may also include measures of humidity, precipitation, and treatment block altitude. It might even include as a factor whether the plot lies on a northern or southern slope. Or it may involve no inputs at all, being just a fixed estimate.

An example of improved planning resulting from improved models is FSCGB model application in the more detailed planning of a spray project, leading to specification of swath width, flight altitude, number of swaths, and location of sampling lines and trees.[3]

As with policy formulation we see that forecasting and planning activity is basically unchanged as a model is adjusted, but must be revised as a model is enriched.

We also point out that there is a practical limit to the reduction in prediction error which may be achieved, since much error is attributable to input survey data errors, which are inevitable with finite surveys.

[3] Rafferty, J.E., and R.K. Dumbauld, Selection of Spray Operations Criteria for the Withlacoochee State Seed Orchard Project, Report No. 80-8, Methods Application Group, Forest Insect and Disease Management, U.S. Forest Service; Davis, California, June 1980.

Execution. The suppression manager generally employs models in the planning of field surveys and suppression operations -- not in their execution. So we generally do not look for improvement in execution as a result of improved models and data bases. Nevertheless, it is conceivable that models could be applied during actual project execution (e.g., feeding real-time meteorological and aircraft data into an on-site installed FSCBG model in order to dictate flight profile modifications), but this would seem to be far into the future.

Evaluation. There are many aspects of evaluation. We see the evaluation of suppression management tools, such as pesticides and forecasting models, in terms of statistical hypothesis testing on the model parameters. For example, the question of whether pesticide A provides better foliage protection than pesticide B may be construed as a question of whether, for a given set of inputs, the statistical model for pesticide A shows significantly better foliage protection than does the model for pesticide B. The answer to the real world question is then only as good as the models. Improved models therefore mean improved evaluation of tools research.

Research. Models constitute the suppression management community's understanding of the pest threat and the suppression management process. The models may suggest new suppression management strategies and tools. They may also be used to test such proposals in a preliminary way.

Areas where models perform poorly are areas not well understood, and can be targeted for basic research.

Objective mathematical models and computer programs are very important to research, since they provide a basis for precise, objective communication of concepts and understanding. If the models are objective, then the understanding embodied in the models can be objectively tested by experiment. This is the essence of the scientific method.

A GENERIC SUBSYSTEM FOR AERIAL APPLICATION OF PESTICIDE

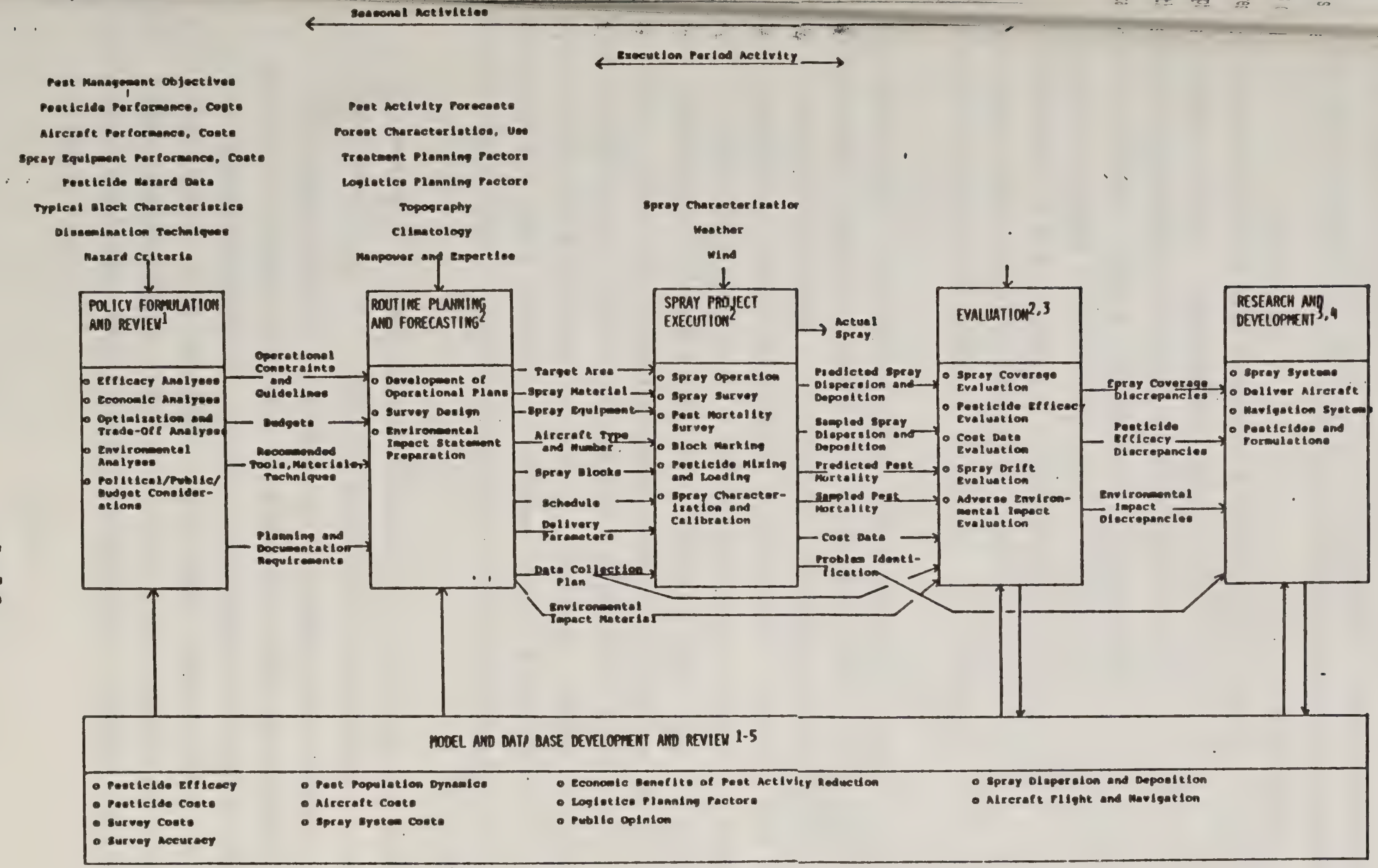
General

The subsystem description developed below will serve as a vehicle for systematically appreciating potential applications of improved aerial spray dispersion and deposition models in forest pest suppression management. The subsystem is built on concepts developed in the previous section, with special emphasis on the role of models and data bases -- whether objective and quantitative or subjective and experiential.

The Generic Subsystem

A generic subsystem for aerial application of pesticides is depicted in Figure A-2. The five general activities involved in pesticide application are depicted by the boxes running across. Supporting these activities is the on-going activity of model and data base development and review. In the past this was not recognized as an activity in its own right, since it was simply "learning by experience," and "keeping abreast of research." Now, with development of mathematical models and computer algorithms addressing topics such as those indicated in Figure A-2, model and data base development and review stands out as a distinct support activity. These six main activities are now considered in more detail.

(1) Policy Formulation is an on-going activity performed by the appropriate supervisory or policy staff in USDA, USFS, EPA, or parallel state organizations. Inputs to this activity include the pest management objectives promulgated at the highest bureaucratic levels, hazard criteria established by cognizant health and environmental offices, spray system and aircraft performance characteristics, pesticide formulation and efficacy data, information on pest biology, typical spray block characteristics, pesticide dissemination techniques, and price estimates for manpower, pesticides, aircraft, and support.



Notes: 1 - Policy staff at USDA, USFS (FI&DM/WO, S&PF District HQ, NF Regional HQ), EPA (HQ, District Offices), Cognizant State Forestry Bureaus, Cognizant State Environmental Protection Offices, etc.

2 - Project supervisor and staff at State or National level.

3 - Independent researchers from research arms of USFS, EPA, and parallel state organizations.

4 - Research scientists and engineers in USFS, EPA, and parallel state organizations; also at universities and at chemical material and aerial spray equipment development and production companies.

5 - Systems analysts, operations researchers, and math modelers in USFS, EPA, and parallel state organizations; also at universities.

FIGURE A-2

GENERIC SUBSYSTEM FOR AERIAL APPLICATION OF PESTICIDES

The responsible policy-makers often undertake or commission studies and analyses as part of the review and initiation of policies, and such analysis employs models and data bases, either implicitly or explicitly.

Policies may range from general guidelines and constraints on pesticide application, to recommendations and purchase contract authorization, pesticides, services, or systems. Handbooks on pesticide application, dictating flight parameters, weather constraints, buffer zone requirements, and so forth, come from this type of policy analysis. Policies are generated to be long term, and will generally stand for several seasons until review is triggered by emerging technology or political consideration.

(2) <u>Routine Planning and Forecasting</u> refers to the development of operational plans for specific aerial spray operations and the attendant surveillance activities. This is the responsibility of the project supervisor and staff at the state or national level. Two major classes of inputs go into this activity. First are the guidelines, constraints, budgets, and requirements within which the pest manager must operate. Second are the pest activity forecasts, descriptions of infested areas, and treatment planning factors. The planners must use this information to determine what areas to treat and to develop detailed plans and schedules for aerial spraying and associated survey activity.

Where policy guidance is detailed and explicit, planning may involve little more than rote application of codified decision procedures. Under more general policy guidance the pest manager is at more liberty to make adjustments for special situations. In that case he makes adjustments based on ad hoc analyses, either implicitly or explicitly exercising models and employing data bases. This is common when policies have essentially been the codification of standard operating procedures, designed to free

the pest manager from the chore of detailed analysis for every potential spray project, and not meant to be rigidly applied.

A major product emanating from this planning and forecast activity is material for inclusion in an environmental impact statement. Frequently models and data bases are employed in the preparation of this material.

(3) Spray Project Execution is conducted, generally, by contractors under the supervision of the project manager and his staff. The primary inputs to this activity are the plans and contracts developed during the planning phase. Current and next-day weather and wind data and forecasts are also input in order to finalize flight profiles and spray survey design. Spray nozzles, application rates and other parameters might also be varied here as the result of spray characterization tests. Such adjustments involve exercise of codified rules, or even implicit models of spray behavior.

(4) Evaluation is generally accomplished in two time periods, the first being the hours and days immediately following the spray, and the second being a protracted period of weeks to years which the site is revisited, or foliage protection is examined through aerial survey or photography, or reports of adverse environmental impact are attributed to the spray project in question. Such evaluation may be accomplished by the cognizant pest manager and his staff (wearing the hats of methods researchers), or by independent researchers from other forest management or environmental protection offices.

Evaluation is generally geared to the discovery of discrepancies between predicted and measured performance of pesticides and spray systems. Such discrepancies can either be caused by inaccurate measurement of the variables used to feed the predictions, or by genuine deficiencies in the prediction models. Where the latter cause is suspected, a need for further research is identified.

It is also conceivable that the evaluation phase will be geared to estimating parameters of a yet uncalibrated model, although this is more normally done during research projects rather than routine operations. Spray characterization for a new atomizer or pesticide sticking agent would fall into this category.

(5) <u>Research and Development</u> is an on-going activity ideally channeled to mitigation of problems during any of the preceding pest management activities. These problems might include such things as excessive application costs, overly restrictive environmental constraints, scheduling problems due to poor weather conditions, skips and misses, or inaccurate prediction of spray deposition and drift.

(6) <u>Model and Data Base Development and Review</u> is another on-going activity, though as mentioned earlier it receives little or no attention. Yet implicit models and data bases are used in policy formulation and review, routine planning and forecasting, and in evaluation design. Some models and data bases are rather obvious, such as those for predicting pesticide efficacy and costs. Others are not so obvious, such as those permitting the pest manager to predict public and bureaucratic response to defoliation on untreated recreation areas on the one hand, or fish kills from spray misses on the other. As mathematical and computer models see increased use in forest pest management the model and data base development and review activity should achieve greater visibility.

APPENDIX B
THE FSCBG COMPUTER PROGRAM

INTRODUCTION

The FSCBG (Forest Service, Cramer-Barry-Grim) Computer Program is a system of computerized models for predicting aircraft spray dispersion and deposition above and within forest canopies. This system of models will be used as the point of departure for construction of an Aerial Spray Planning and Analysis System (ASPAS).

It is the purpose of this appendix to describe the FSCBG Computer Program, to comment on its state of development, to indicate scope and restrictions, and to identify perceived deficiencies and directions for improvement.

Much of the material in this appendix is taken directly from the U.S. Forest Service (Methods Application Group) report documenting the FSCBG computer program.[1] The reader should refer to that report for more detail.

BACKGROUND

The USDA Forest Service uses aerial spray applications to prevent and suppress tree damage due to pest infestations. As part of an extensive program to develop and evaluate pest management systems, the USFS is interested in achieving an improved understanding of the behavior of spray material from the time spray is released from the aircraft until it has been deposited, or in the case of spray drift, dissipated to concentration/dosage levels that are environmentally insignificant. Because mathematical spray dispersion models are useful in determining interactions of the many factors affecting spray

[1] Dumbauld, R.K., J.R. Bjorklund, and S.F. Saterlie, Computer Models for Predicting Aircraft Spray Dispersion and Deposition Above and Within Forest Canopies: User's Manual for the FSCBG Computer Program, Report No. 80-11, U.S.D.A. - Forest Service, Forest Pest Management Methods Application Group; Davis, California, October 1980.

operations, the USFS has supported the application and development of these models over the last decade. Simplified aerial line source models developed for the U.S. Army were applied early in the decade to evaluate swath widths and application rates for use in pilot tests of insecticides under consideration at that time for control applications in western forests.[2,3,4] In 1977 the H.E. Cramer Company provided deposition profile calculations to assist the State of Maine Bureau of Forestry in predicting drift from spray blocks into exclusion areas (streams, homes, etc.) in the vicinity.[5] Under the sponsorship of the USDA Expanded Douglas-fir Tussock Moth Research and Development Program, work began in early 1977 on the development of a technical data base for use in applying mathematical dispersion models to USFS spray projects and the refinements and adaptation of existing models to predict spray behavior above and within forest canopies. This work resulted in the develop-

[2] GCA Corporation, Model Estimates of the Deposition of Aerial Spray on a Forest Canopy, Technical Note, Contract No. DAA-DO9-71-C-0003 with U.S. Army Dugway Proving Ground; Dugway, Utah, 1971.

[3] H.E. Cramer Company, Model Estimates of Deposition and Concentration for the 1973 Field Tests of Insecticides on Pine Butterfly Larval Population in the Bitterroot National Forest, Technical Note prepared under Contract No. DAA-DO9-71-C-0003 with U.S. Army Dugway Proving Ground; Dugway, Utah, 1973.

[4] Dumbauld, R.K., H.E. Cramer and J.W. Barry, "Application of Meteorological Prediction Models to Forest Spray Problems," presented at the USDA Forest Service Workshop, Aerial Application of Insecticides Against Forest Defoliators, Missoula, Montana, April 1974, DPG Document No. DPG-TR-M935P, U.S. Army Dugway Proving Ground; Dugway, Utah, 1975.

[5] Dumbauld, R.K. and J.R. Bjorklund, 1977: Deposition Profile Calculations for the State of Maine 1977 Spray Program. H.E. Cramer Company, Inc. Technical Report TR-77-310-01 prepared for Litton Aero Products, Woodland Hills, California and the State of Maine Bureau of Forestry; Augusta, Maine.

ment of the CBG computerized spray dispersion model and the comparison of model predictions with measurements made during selected USFS spray programs.[6] The CGB computer program has recently been applied in the selection of swath widths, application rates, and aircraft altitudes for the conduct of a pilot project in the Withlacoochee State Seed Orchard Project[7] and has assessed model perfomance in that project.[8] The USFS has also sponsored the use of the CBG model to select swath widths and spray altitudes for specific spray aircraft planned for use in the Maine 1980 Spray Program.

The FSCBG computer program is comprised of two major parts. The first part simulates the deposition of spray drops at the top of a forest canopy. The second part simulates the penetration of spray drops into the forest canopy.

During the most recent phase of FSCBG computer program development these portions and the associated submodels were integrated in a modular fashion to ensure that further updates in the various calculation procedures could be more easily accomplished. Also, many calculations for deriving input parameters,

[6] Dumbauld, R.K., J.E. Rafferty and J.R. Bjorklund, Prediction of Spray Behavior Above and Within a Forest Canopy, Special Report Under Contract No. 19-276, Pacific N.W. Forest and Range Experiment Station, Portland, Oregon. Published by Methods Application Group, USDA Forest Service; Davis, California, 1977.

[7] Rafferty, J.E. and R.K. Dumbauld, Selection of Spray Operations Criteria for the Withlacoochee State Orchard Project, Report No. 80-8 under Contract No. 53-01S8-9-6260, Methods Application Group, USDA Forest Service; Davis, California, June 1980.

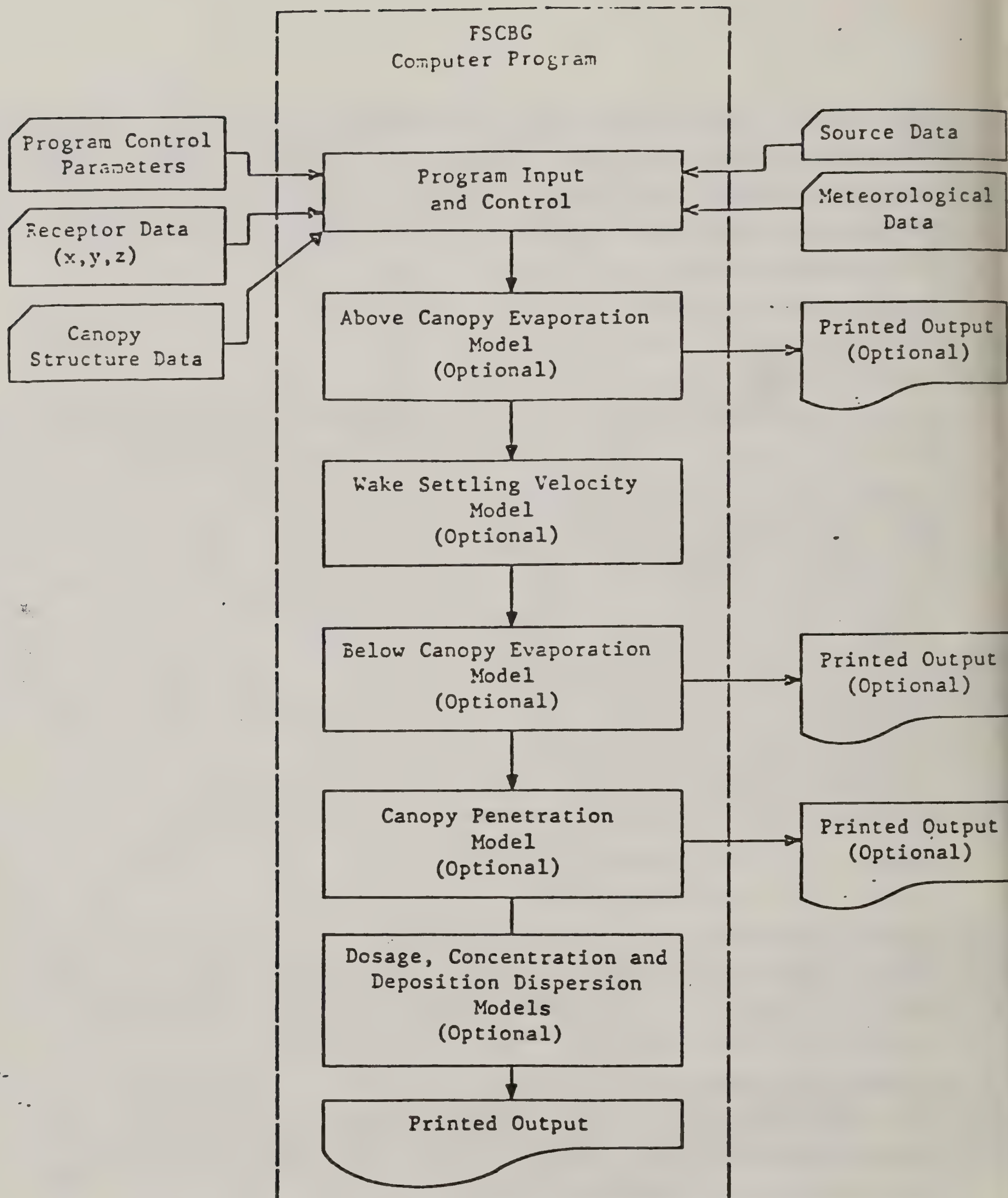
[8] Rafferty, J.E., R.K. Dumbauld, H.W. Flake, Jr., J.W. Barry, and J. Wong, Comparison of Modeled and Measured Deposition for the Withlacoochee Spray Trials, Report No. 81-3, under contract No. 53-9158-9-6260, Methods Application Group, USDA Forest Service; Davis, California, February 1981.

such as the gravitational settling velocity of drops, are performed automatically, on user option, by the new program. Finally, the program was extended to include the effects of spray drop evaporation on the spray deposition patterns and drift concentration/dosage levels.

DESCRIPTION

Overview.

The FSCBG computer program implements an aircraft wake-settling velocity model, line-source dispersion models, a drop evaporation model and a canopy penetration model to calculate the mass and droplet deposition above and below a forest canopy downwind from multiple aircraft spray lines or swaths. It also calculates dosage and peak concentration, but only above the canopy. The program is written in FORTRAN IV and is designed for implementation on a UNIVAC 1108 computer, although the program is easily adapted to other computer systems. The computer program requires 32K words of core storage. Figure B-1 is a schematic diagram showing the major components of the FSCBG program. As indicated in the figure, program control parameters, as well as source and meteorological data are input to the program via card image. The input requirements of the program are discussed later in this section. Definitions of the meteorological and source inputs and their relationships to the various program models are also indicated. Figure B-1 shows that the user may select a number of model options. The Above Canopy and Below Canopy Evaporation Model option allow the user to specify whether or not drop evaporation is to be included in a calculation of concentration, dosage and deposition. If the user selects a drop evaporation option, the program automatically calculates the change in drop diameter with time, using a polynomial expression fitted either to empirical data or theoretical calculations. The Wake-Settling Velocity Model option permits the user either to input



Source: Dumbauld, Bjorklund, Saterlie, 1980. Op. cit.

Figure B-1. Schematic Diagram of the FSCBG Computer Program

the aircraft wake-settling velocity directly or to input the aircraft weight, wing span and ground speed which the program uses to calculate the aircraft wake-settling velocity. The Canopy Penetration Model option permits the user to calculate the fraction of material presented at the canopy top, penetrating the canopy and reaching up to 10 levels within and below the canopy, including the ground. Finally the Dosage and Concentration Dispersion models permit the user to calculate dosage, concentration, and area coverage of user specified dosage and concentration levels above the canopy and below the height of elevated inversions. Dosage and concentration cannot be computed below the canopy by the current FSCBG computer program. The Deposition Dispersion Model allows the user to calculate deposition and deposition area-coverage at any height below the height of elevated inversions, including heights below the canopy top when the model is used in conjunction with the Canopy Penetration Model. In its present configuration, the FSCBG computer program can calculate the dosage, concentration and deposition at a maximum of 737 receptor coordinates downwind from a maximum of 100 line sources.

In the following paragraphs each of the FSCBG models will be described in very general terms, to give the reader a rough appreciation for the analytical methodology and capabilities. These models are discussed in a different order than presented in Figure B-1. The order of discussion corresponds roughly to the historical sequence of development and the consequent logical ranking.

Dosage, Concentration and Deposition Dispersion Models.

The spray dispersion models incorporated within the FSCBG computer program are similar to the aircraft spray models developed previously for the U.S. Army Dugway Proving Ground,[9]

and are based on the generalized diffusion model concepts developed earlier.[10] These models employ a discrete distribution of spray drop sizes, computing dispersion of each drop size separately and then summing over all drop sizes to get total dosage, concentration or deposition. The to assume the existence of a mixing layer above the spray aircraft which reflects all drops (dispersed up by turbulence) down. Reflection is also assumed at the ground, but this occurs at a fractional rate dependent on drop size.

The actual expressions for dosage, concentration, and deposition involve complicated double summations, one summation taken over the finite number of drop size categories, and the other summation taken over the infinite number of possible reflections. The summations are evaluated numerically, with computation terminated when truncation error appears negligible. The terms within the summation are characteristic of gaussian diffusion models for finite line sources.

Although above-canopy dosage and peak concentration are available from these models, deposition at the top of the canopy is of primary interest in the FSCBG program, and serves to drive the canopy penetration model. In the absence of canopies, deposition can be directly calculated for the ground surface.

Evaporation Model.

The FSCBG computer program has a number of options allowing the user to account for the effects of the evaporation of drops in the calculation of dosage, concentration and deposition. The first step in the calculation of evaporation effects is the specification of the time-rate change of the drop diameter for the initial j drop-size categories. The program user has the option of selecting an automated procedure for the theoretical calculation of the time-rate change in drop diameter, or of supplying a quadratic equation specifying the change of drop

diameter with time t after release. The theoretical calculations involve iterative solution of a number of equations relating the physical properties of liquid drops and the surrounding air vapor and numerical solution of a simple difference equation.

Canopy Penetration Model.

Grim and Barry[11] developed a mathematical model to calculate the percentage of material of a given drop-size category j which, after entering the forest at the top of the canopy, is retained at various levels within the canopy. The model is based on a Monte Carlo technique where a large number of drops in each size category are passed along a trajectory through a simulated forest with trees assigned to equal areas according to the density (stems per acre) in the forest being simulated. The drop trajectory is a function of the gravitational settling velocity, which varies along the trajectory when the evaporation model is used, and the mean wind speed at various levels within the canopy. As a drop proceeds along the trajectory, each tree is randomly displaced within the assigned area in the plane of the horizon and calculations are made to determine if the drop intersects the tree envelope and, if an intersection occurs, whether the drop strikes a tree element. When the drop strikes a tree element, a tally is recorded for the height interval within the canopy where the "hit" occurs and for all greater height intervals. Drops proceed along the trajectory until a hit occurs or until the trajectory intersects the ground. After the specified total number of drops in the size category have passed along the trajectory, the tally number within each height interval is divided by the total number of drops to obtain the percentage of

[11] Grim, B.S. and J.W. Barry, A Canopy Penetration Model for Aerially Disseminated Insecticide Spray Released above Coniferous Forests, Final Report under MEDA Project No. 2425, Forest Service Equipment Center; Missoula, Montana, 1975.

drops reaching the given height interval. The total number of drops passed along the trajectory required to achieve a stabilized solution (percentage penetration) is a function of the steepness of the trajectory, with more drops being required for size categories with large settling velocities. In the FSCBG program, 500 drops in each size category are passed along the trajectory.

The process describes above is repeated for every drop passed along the trajectory and the final percentage of material penetrating to a given height interval determined by dividing the number of recorded hits in the height interval by the total number of drops in all j^{th} size categories passed along the trajectory. When the evaporation model is used, the mass or number of drops reaching a given level in the canopy is further adjusted to account for losses due to evaporation. The computer program also permits the user to simulate a multi-storied canopy of up to three tree heights, with different input characteristics possible for each tree or story height.

Aircraft Wake Model (Wake Settling Velocity Model).

During a short time period after spray is released from an aircraft, the vortices formed by the wings and propellers of fixed-wing aircraft and by helicopter rotors principally control the growth of the spray cloud. Except for the lateral translation of the vortex system by a crosswind, the vortices also control the position in space of the spray cloud and the amount of material which may be deposited on the underlying surface directly below the flight path. There are a number of sophisticated models presented in the literature describing conventional aircraft wake action and associated computer programs. Such complex programs would, if incorporated with the dispersion, evaporation, and canopy penetration codes in the FSCBG program, greatly increase the computation time required to estimate deposition patterns. It appeared that simpler wake models and computer codes would soon be available as products of a USFS/NASA

program on wake effects. For these reasons, the FSCBG program was designed so that wake computer codes could easily be modified and/or added to the program. Since the importance of wake effects was recognized, the current version of the FSCBG program contains an interim wake-effects model the developers found useful in previous USFS work.

The model is based on an expression for the sink rate of the vortex system, involving aircraft speed, weight, and wing (rotor) span. From this, together with the wind vector, the model determines when and where the vortex descends to the canopy. However, it is assumed that this descent involves only those drops which are so small that they would otherwise fall more slowly. The model then apparently develops a corrected, or effective source height for each category of these lighter drops. These effective source heights are then used to adjust the dispersion models to account for wake settling through a virtual source concept. For drops which would naturally fall more rapidly than the wake, no such correction is applied.

Adjustment of Deposition Calculations for Evaporation.

When no evaporation occurs, the calculation of deposition is relatively straightforward because the gravitational settling velocity is invariant with time. However, when evaporation occurs both drop size and gravitational velocity vary with travel distance from the source and the deposition calculations become much more comlicated. In order to adequately treat this case, a "reverse tracking" scheme is applied, essentially answering the question: if a drop of a specified size lands in the vicinity of a given receptor, what is the trajectory it would have had to follow, and where would the drop have had to enter the canopy. The program iteratively answers this question, sets an effective settling velocity for the drop, and uses this velocity to adjust the deposition model so that the drop trajectory from the source to the receptor is described, accounting for mass loss through evaporation in the process.

Input Data Requirements.

The data needed to run the FSCBG program is indicated in Tables B-1 to B-5. These data can be categorized by availability and variability as follows:

Readily available, static data: these include physical constants such as the density and latent heat of vaporization of the spray drop liquid. They also include fixed parameters such as aircraft weight and wing span.

Fairly static data measurable with difficulty: these include spray drop size frequency distribution, tree density, and average tree envelope dimensions. Although such data can be measured in a straightforward way, this measurement is quite tedious. It is therefore preferred to use "canned" data sets associated with the aircraft/spray system or forest type, and judgmentally adjust these if necessary.

Quasi-measurable parameters: these include the probability of penetration through a tree, the average collection efficiency of a vegetative element, the average vegetative element diameter, and the time to cloud stabilization. Although it is conceptually possible to develop procedures to measure such variables, they are treated as bulk processes in the model and the characterization of the bulk process with measurements is difficult. One approach is to treat such parameters as variables to be estimated during calibration of the FSCBG model. For example, the probability of tree penetration can be adjusted until the FSCBG program yields results comparable to those observed in field trials.

Easy to measure, near real time meteorological data: These include temperature, relative humidity, and possibly wind velocity at the aircraft and ground levels.

Table B-1

General* FSCBG Program Input Data

- Aircraft wing span or helicopter rotor diameter
- Height of aircraft above ground
- Wind speed above canopy
- Air temperature above canopy
- Air temperature below canopy
- Air density
- Density of spray drop liquid
- Initial drop size frequency distribution

* Used by more than one of the FSCBG models.

Table B-2

Evaporation Model* Input Data

Option 1	Option 2	Option 3
(for water based spray)	(for non-water based spray)	
• Air pressure	• Air pressure	• Constants in equation for time rate of change of drop size above canopy (3 x (number of drop size categories) constants required)
• Molecular weight of air	• Molecular weight of air	• Constants in equation for time rate of change of drop size below canopy (3 x (number of drop size categories) constants required)
• Molecular weight of vapor from the spray drops	• Molecular weight of vapor from the spray drops	
• Relative humidity above the canopy	• Relative humidity above the canopy	
• Relative humidity below the canopy	• Relative humidity below the canopy	
	• Diffusivity of evaporating vapor	
	• Latent head of vaporization	
	• Molal concentration	
	• Thermal conductivity	
	• Vapor pressure at infinity	
	• Vapor pressure equation constants (2 constants required)	

* This model is optional; if not elected, these inputs are omitted, and the drop size distribution does not vary with time.

Table B-3

Wake-Settling Velocity Model Input Data

Option 1	Option 2
• Wake settling velocity	• Aircraft weight
	• Aircraft ground speed

Table B-4

Canopy Penetration Model* Input Data

- Wind speeds in the canopy at quarterly intervals

- Height of canopy for each tree category**

- Probability of drop penetration for a horizontal trajectory through a tree (stem) in a given tree category

- Tree density for a given tree category

Average collection efficiency for vegetative elements or average effective diameter of vegetative elements	for each drop size category and tree category

- Width of tree in given tree category at various heights

* This model is optional; if not elected, these inputs are omitted, and no forest canopy is present.

** Up to three tree categories (varieties) may be used.

Table B-5

Dispersion Model* Input Data

- Line source (spray pass) endpoint coordinates (multiple line sources allowed)
- Spray application (emission) rate
- Rectangular receptor grid coordinates (this grid of "receptors" is useful for examining deposition in or near the spray blocks)
- Additional receptor array coordinates (these additional "receptors" can be used in examining off-site drift)
- Height of calculations**
- Standard deviation of wind azimuth angle
- Standard deviation of wind elevation angle
- Time to cloud stabilization***
- Time over which standard deviation for wind azimuth was determined***
- Standard deviation of spray material distribution along the spray line***
- Lateral and vertical reference distance downwind from spray line where spray cloud has dimensions given by last input*** (this parameter is normally defaulted and computed by FSCBG program)

(continued)

* This model is optional; if not elected, these inputs are omitted and the dosage, concentration, and deposition models are skipped.

** The FSCBG model currently computes deposition, dosage, and concentration at only one height; additional runs of the model can be made to calculate these variables at other heights.

*** These parameters have default values if inputs are omitted.

Dispersion Model Input Data (continued)

- Wind speed shear between canopy and aircraft heights***
- Height of the surface mixing layer
- Wind direction
- Ratio of Lagrangian to Eulerian time-scales to be used in correction for crossing-trajectory effects of heavy drops when evaporation is not occurring***
- Coefficients and break points of the equation giving the fraction of material reflected at the surface as a function of drop settling velocity (11 constants required***)
- Dosage levels in output dosage units for which dosage area-coverage is to be calculated (output specification option)
- Concentration levels in output concentration units for which concentration area-coverage is to be calculated (output specification option)
- Deposition levels in output deposition units for which deposition area-coverage is to be calculated (output specification option)

*** These parameters have default values if inputs are omitted.

Difficult to measure, near real time meteorological data: These include wind speeds in the canopy at quarter intervals, wind speed shear between canopy and aircraft, standard deviations of wind azimuth and elevation angles, and height of the mixing layer.

Operational parameters: These include aircraft height and speed, swath width, flight lines, and perhaps, orientation to the wind. Aircraft type, nozzle type, pump pressure, and pesticide formulation are other operational variables, but these are reflected in other inputs (drop size distribution, application rate, aircraft characteristics, etc.).

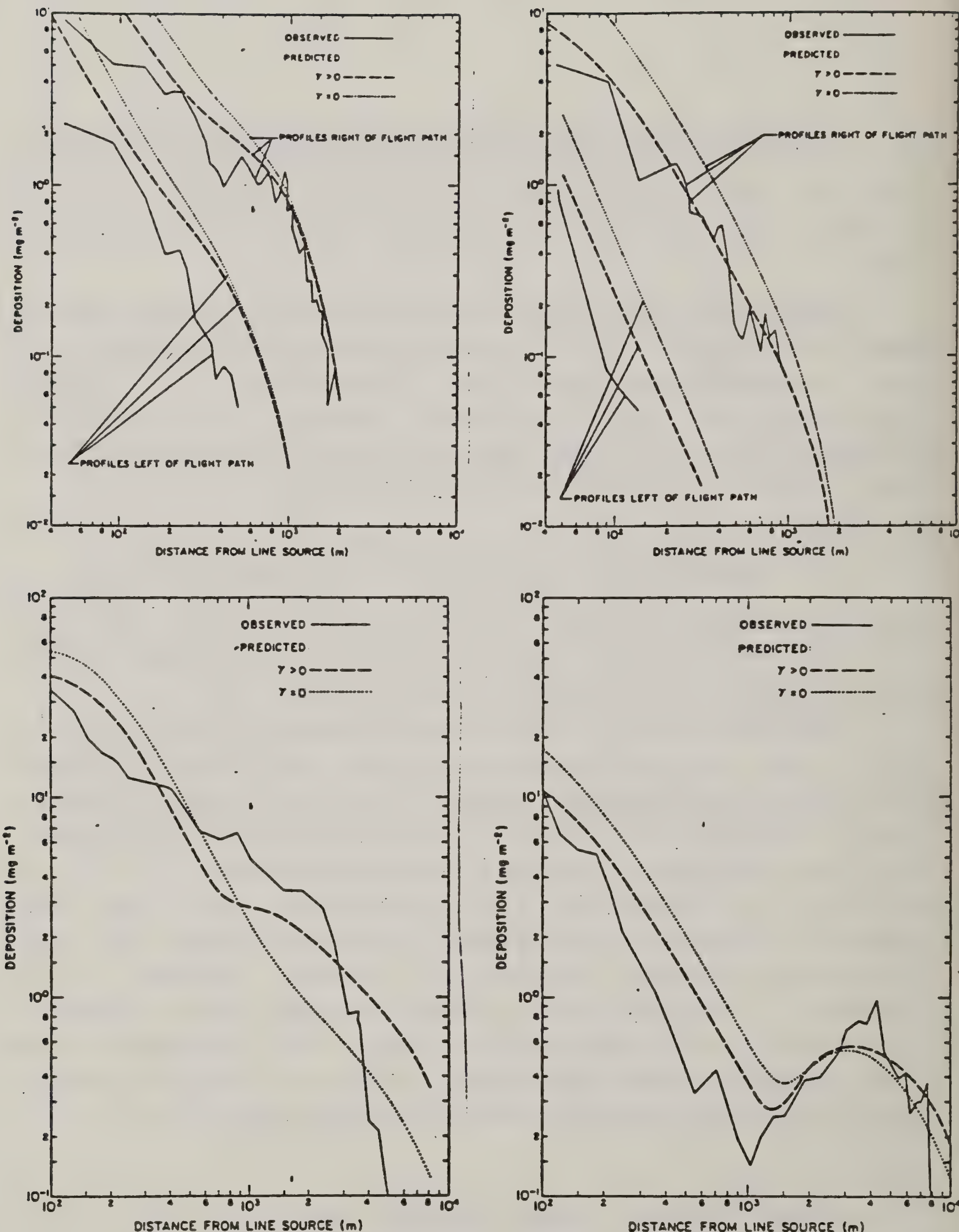
VALIDATION

Some effort has been applied over the years to validating the constituent models of the FSCBG program. In Figure B-2, for example, some dispersion comparisons to observed results in some DC-7B aircraft trials show good model performance.[12]

The recent effort to validate the current FSCBG model in spray trials in the Withlacoochee State Seed Orchard[13] appears particularly well planned, executed, and documented. Typical results are shown in Figure B-3. These results are good considering the complexity of the phenomena being modeled, but are not as good as one would like. If a planner had used these model results in selecting swath widths, he probably would have opted for narrower swaths in order to increase coverage in the "troughs." This would have increased aircraft costs unnecessarily, since, as it turned out, coverage in the troughs was good even for the original swath width. With only very minor adjustment to the wake model, the fidelity was very significantly

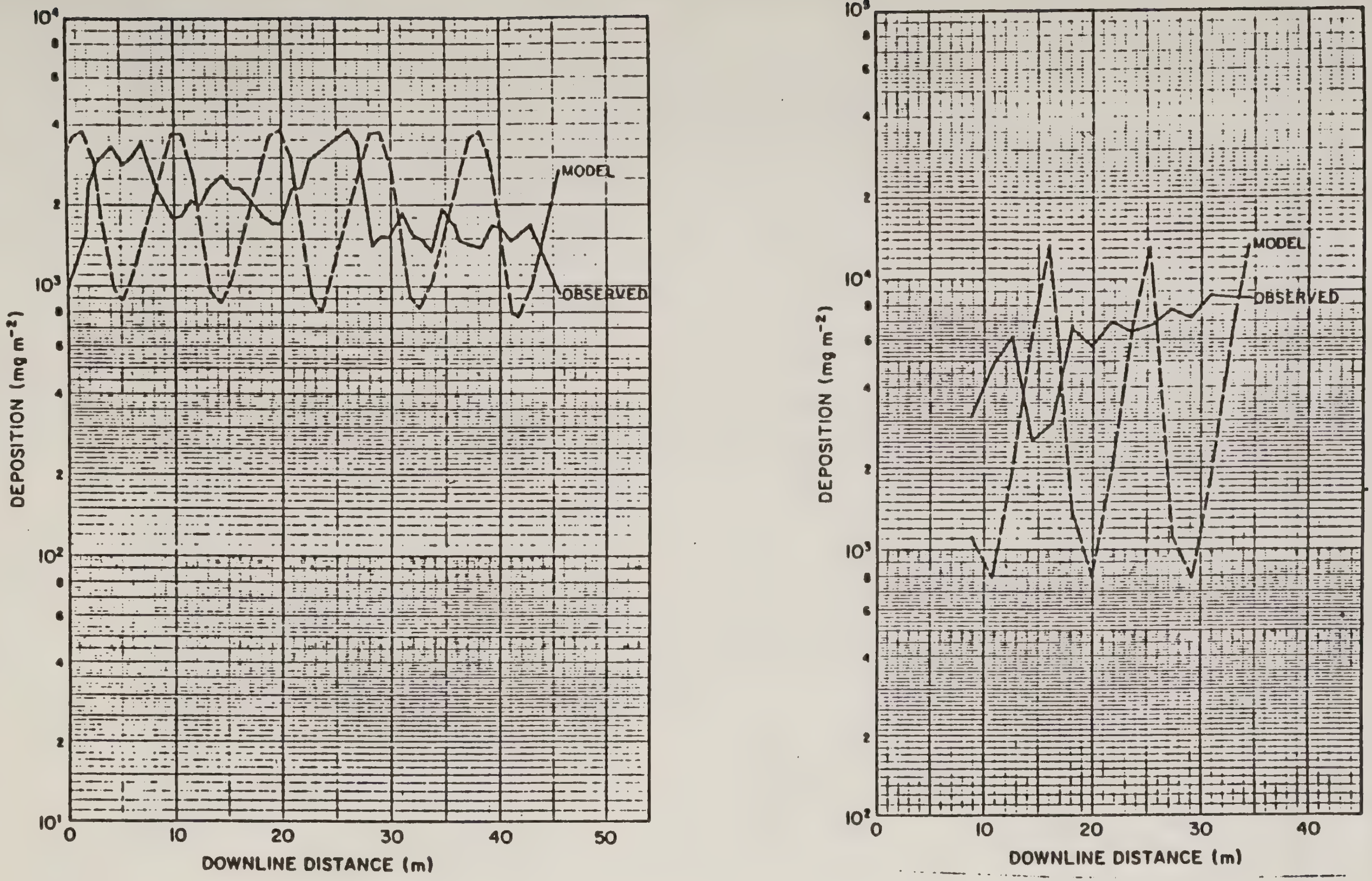
12 Dumbauld, Rafferty, Cramer, 1976. Op. cit.

13 Rafferty, Dumbauld, Flake, Barry, Wong, 1981. Op. cit.



Source: Dumbauld, Rafferty, Cramer, 1976. Op. cit.

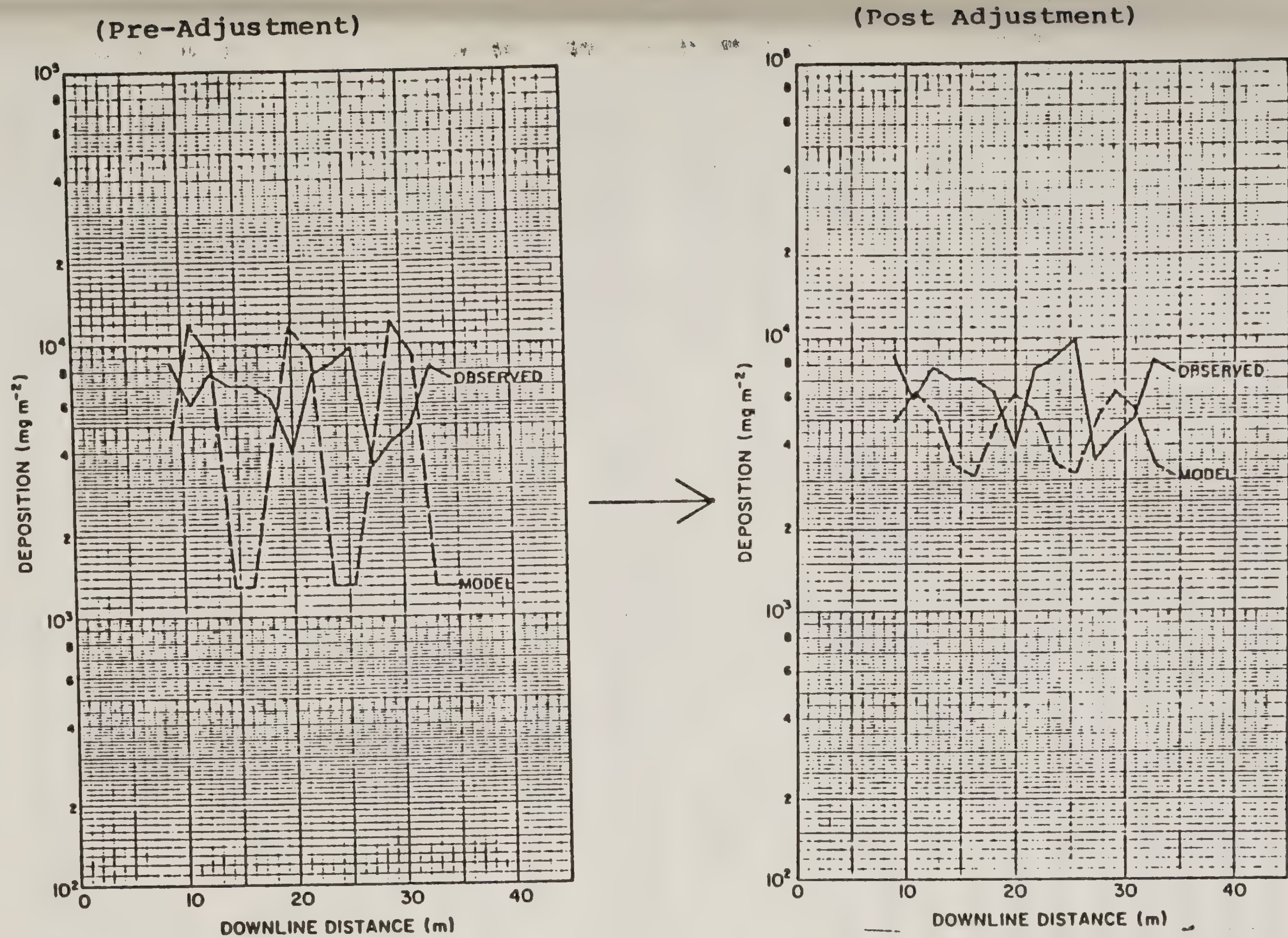
Figure B-2. Performance of Dispersion Model for Some DC-7B Aircraft Spray Trials



Source: Rafferty, Dumbauld, Flake, Barry, Wong, 1981. Op. cit.

Figure B-3. Typical Comparison of Modeled and Measured Deposition for the Withlacoochee Spray Trials

improved (Figure B-4), suggesting that model fine tuning and calibration - vis a vis major model reformulation - may suffice to bring about adequate model predictive performance.



Source: Rafferty, Dumbauld, Flake, Barry, Wong, 1981. Op cit.

Figure B-4. Increased Fidelity Between Modeled and Measured Deposition for the Withlacoochee Spray Trials Achieved Through Adjustment of Wake Model

APPENDIX C
WORK STATEMENTS

This appendix contains suggestions for specification of the tasks which are necessary to implement the recommended enhancements to the system through MOD 2 which were presented in Section IV of the report. The tasks are presented in logical groupings, referred to here as projects. The grouping of similar or directly related tasks will in many cases minimize the effort and expense required to perform them. This is an economy of scale resulting partially from a reduction in the time required to familiarize the worker with the system and the work to be done, but also depending on the time and effort required for coordination of tasks. The precise pattern of grouping should be considered to be quite flexible, and will depend on the availability of funds, time constraints, and the availability of appropriate contractors.

MOD 1 DEVELOPMENT

PROJECT 1. Simplification of Input Data Handling, Development of Interactive Program Control, and Development of Enhanced Output Display Capabilities.

TASK 1: Simplified Input of Droplet Spectra.

Droplet size categories and the distribution of spray mass among them should not have to be input by the user for each program run. They should be stored by the system for later call-up based on aircraft type, spray equipment, and formulation.

The contractor will design appropriate data storage and control structures for this purpose. The design will be submitted to the contracting officer for approval. Upon approval of the design, the contractor will perform the necessary coding to incorporate this improvement into the ASPAS system. The contracting officer will make available existing spray source data which the contractor will enter into the data base.

TASK 2: Simplified Input of Stand Description Data.

The parameters describing the structure of the forest canopy should not have to be input by the user for each program run. They should also be stored for later call-up. The system will initially only contain stand descriptions for a few scenarios, but a data base system should be developed to allow selection of the necessary parameters for canopy description based on a simple stand classification system, which will be developed at a later time.

The contractor will design appropriate data storage and control structures for this purpose. The design will be submitted to the contracting officer, and upon his approval the contractor will perform the necessary coding to incorporate this improvement into the ASPAS system. The contracting officer will make available existing stand description data, which the contractor will enter into the data base.

TASK 3: Deposition Calculations for All Heights Simultaneously.

As the FSCBG program is currently structured, deposition, dosage, and peak concentration calculations are output for one level at a time. Data describing an entire height profile through the canopy should be made available.

The contractor will design appropriate data storage structures which will be convenient in terms of availability for inclusion in calculations by new modules of the program, and for flexible output formats. The contractor will design and code the necessary programming to create and store the deposition, dosage, and peak concentration data. It should be stored in a form which allow easy addition of new items (such as a measure of mortality), and which is suitable for output to mass storage media for future use by the display module.

TASK 4: Creation of Summary Display Programs.

The contractor will design an interactive graphical display program which will allow the user to select from among various displays based upon data stored at the completion of a model run. The displays made available should include graphs of vertical profiles at points selected by the user, contour diagrams and tabular output. The program should be able to create displays of deposition, concentration, dosage, and target pest mortality. It should be flexibly designed to allow easy addition of new variables. It should be operable on a portable terminal, with the capability to produce hard copies.

Both the design of the program and choice of hardware type will be submitted to the contracting officer for approval.

Upon receipt of approval, the contractor will code the necessary programming to implement the display capability.

TASK 5: Interactive Program Control.

The contractor will design interactive software to setup all necessary input data and control parameters, submit batch simulation runs, and call the graphical display program developed under Task 4. The software should allow entire sets of input data and control parameters from previous runs to be recalled, any parameters changed at will, and re-run. The user should have the option of storing both the input and the output in mass storage files for re-use at a future date. If the user does not wish to begin with an existing input file, then the program should ask him a series of questions which would indicate which simulation options are desired and which data are to be used. The operator should be able to call up existing sets of input data describing droplet spectra and stand descriptors. If these or other major subsets of the data (such as meteorological variables, flight paths, or receptor points) do not exist in the data base then the operator should be able to ask for an input

prompting routine. Checks should be made on the input data and error messages provided when appropriate. The program design should be flexible to allow incorporation of future changes in required input and program operation. The design will be submitted to the contracting officer for approval, after which the necessary coding will be performed to implement the design.

Machine and Language Requirements

In order to maintain consistency and compatibility with the current MOD 0 ASPAS (FSCBG) program, the softare produced under this project should be written in FORTRAN for use on the Forest Service UNIVAC computer in Fort Collins, Colorado. All software must be demonstrated on that facility before acceptance by the contracting officer. Program listings including ample comments will be supplied, along with supporting documentation, describing the programming approach and details of the coding.

Level of Effort

The level of effort required to complete the five tasks is estimated to be six man-months.

PROJECT 2. Improvements to the Simulation

TASK 1: Improvements in the Impactation Model

The Barry-Grim canopy penetration model as it is now implemented relies on Sell's Law to describe the impaction of spray droplets on foliage elements. The impaction model should be revised to take advantage of more recent experimental and theoretical results, such as those reviewed by Golovin and Putnam (1962). The resulting routine for predicting impaction efficiency should account for the various geometries of vegetation elements, including hardwood leaves.

TASK 2: Effective Wind Speed Correction.

The Barry-Grim canopy deposition model is based on the assumption of a constant wind velocity at any given height within

the canopy. In reality, winds within a forest canopy ordinarily vary quite singificantly over both time and space. The effect of varying wind velocities should be considered in the prediction of impaction efficiencies, as noted by Bergen and Waite (1976) in a study involving paired-cylinder collection devices. This is because the impaction efficiency varies approximately as the root-mean-square of wind speed. Consequently, although average wind velocities may be adequate to describe the ballistic trajectory of droplets, a correction factor should be introduced to the impaction model to account for non-uniformity of the wind velocity. This will require a consideration of the literature on variability of wind within forest canopies.

TASK 3: Alter the Program to Allow Model Runs With Any Flight Pattern

The program can already describe various patterns of flight lines on a horizontal plane, but the altitude should also be allowed to vary from one line to the next, this shoulud be a simple modification, which would allow analysis of some different cases, for example: 1. What is the effect of lowering the flight altitude of the most downwind pass over a spray block, in an effort to avoid off-site drift? or 2. Would deposits be more uniform on the up-wind edge of a spray block if the altitude were lower but the flight lines were closer together?

TASK 4: Alter the Simulation to Represent Forest Edge Effects Beyond the Canopy

This task will consist of an alteration to the Monte-Carlo canopy penetration simulation to allow representation of spray behavior at the edge of a forest canopy, such as would occur at the edge of a clearing or at the shoreline of a lake. The revised simulation should repreent: (1) the canopy ending at a boundary line, (2) increased density of vegetation along the boundary, and (3) a different wind speed beyond the boundary.

TASK 5: Alter the Simulation to Perform Deposition Accounting by Tree Type.

The Barry-Grim canopy penetration model as now represented in the FSCBG program allows three distinct tree types to be considered, but deposition statistics do not differentiate between these types. The program should be changed to explicitly represent deposition for the different types (which need not necessarily represent trees, but could for example be hardwood brush).

This will be necessary for the subsequent development of mortality prediction models for some insects, which may attack one tree type over another or behave differently on one tree than another. The pest manager may also wish to protect one species of a tree rather than another, or he may aim herbicide applications at one type of tree.

TASK 6: Slope Correction for Canopy Penetration.

Although the current canopy penetration model does not include an explicit representation for sloping topography, this in itself is not of great consequence. This is because even on steep slopes the winds generally follow the contour of the land, so that a droplet requires the same amount of time to fall to the ground from the top of the canopy (assuming a simple laminar flow) regardless of the incline. Height in this case must simply be interpreted truly vertically rather than as the distance normal to the ground. However, the angle of attack of droplets passing through the tree envelopes will not be accurately represented in the present simulation. A correction for this should be added to the program.

Requirements

Before actual coding required under the above tasks begins, the specific plan for doing so must be discussed with the contracting officer, and his approval given. Work under these

tasks will have to be coordinated with other related projects. Data input, program control and output display must be designed to reflect the methodology developed under Project 1.

The software produced under this project should be written in FORTRAN for use on the Forest Service's UNIVAC computer in Fort Collins. All software must be demonstrated on that facility before acceptance by the contracting officer.

Program listings including ample comments will be supplied, along with supporting documentation describing details of the coding and assumptions made in the underlying theory or analysis.

Level of Effort

The level of effort required to complete the six tasks is estimated to be 28 man-weeks.

PROJECT 3: Improved Fitting of Canopy Penetration Parameters, and Testing of Evaporation Module.

TASK 1: Validation of Evaporation Routine Using Existing Data.

The evaporation module of the current ASPAS proram should be validated by studying the conformity of model predictions to available field study data.

A statistical analysis of the errors of prediction should be performed to determine their expected magnitude and to determine if systematic errors exist. If unacceptable errors are present, then opportunities for improvement of the predictions by adjustment of model parameters or alteration of the model itself should be investigated.

TASK 2: Calibration of Impaction and Probability of Penetration.

The Barry-Grim canopy penetration model originally made use of Sell's Law to describe inertial impaction of spray droplets on foliage elements. This model has been revised under a previous

task with the objective of obtaining a more accurate representation based on available literature regarding the theory of inertial impaction. The ASPAS must now be calibrated with respect to both the impaction model parameters and the probability of penetration. Existing field study data will be used.

Data Source

Data to support this analysis will be supplied by the Forest Service. The applicable data are expected to consist of deposit monitoring results from the Withlacoochee State Seed Orchard spray trials (Rafferty et al., 1981) and a Kaibab National Forest Study. Both of these data sets deal with water-based sprays.

PROJECT 4: Development and Implementation of Biological Measures of Effectiveness

TASK 1: Development of Simple Insecticide Measure of Effectiveness

The objective of the Phase I BEM development is to provide a near term method for estimating expected pesticide efficacy. With relatively minor enhancements it would appear as though the Force et al. model well suits this objective in its current state, relative to the two insect species for which the model was developed, and to plant species receiving herbicide treatment. Focusing first upon insecticide treatments, the principal model alteration recommended is to provide the capability of outputs to be expressed in terms of a probability distribution. Such a change will allow greater flexibility in program planning and decision-making. It will allow for the calculation of marginal costs and benefits caused by changes in application parameters via the insecticide dosage variable. A simple procedure whereby percent mortality estimates are grouped into classes of a given width, with each class described by an associated probability of occurence, would very likely be the most desirable.

A second area of short term enhancement involves making the model applicable to a number of different heights within the canopy simultaneously. Estimates of mortality for different heights are necessary in the determination of objective droplet size which is a factor greatly influencing many application characteristics, particularly canopy penetration, deposition, drift hazard minimization, and, of couse, target mortality. In order for this to be accomplished, alterations to the FSCBG program to allow for deposition predictions for all heights within the canopy simultaneously, as called for under Project 1, must have been undertaken. In addition, further investigation into the distributions of target species within the canopy in terms of both the physical distribution of individuals within the canopy, and the life cycle stage distribution over the population which is already accounted for in the model is necessary.

TASK 2: Development of Herbicide Measure of Effectiveness

With respect to application of the model to herbicide treatments, the model should be simplified to account for both the sesile nature of the target, and for the different response to toxicants (e.g. no genetic resistance, etc.). Other model enhancements already noted with regard to insect pests also apply here, namely expression of outputs in terms of probability distributions, and applicability to different tree heights simultaneously. This is particularly important with respect to hardwood species which are distributed at all heights within the canopy. A more sophisticated, yet likely feasible in the short term, addition is the development of a response index similar to that recommended with respect to insect species genetic response. Again, this need not be an elaborate physiological response modeling effort. The objective is to produce a series of indices which indicate relative responses to herbicide treatments of the various economically important plant pests. Development of these indices can be accomplished through either physical simulation

(e.g. wind tunnel tests) or through analysis of existing program data, if such data proves sufficient. These indices of expected response of plant species would then be essentially "tempered" by the variables and associated probabilities of the simplified mortality model.

TASK 3: Development of Near-Site Drift Measure of Hazard

One or more explicit measures of the hazard of applied pesticides to non-target organisms within and near spray blocks must be developed for the system. The appropriate measures must be chosen in consultation with Forest Service pest and environmental managers, with a consideration of:

- the particular chemicals most likely to be used in Forest Service projects, their toxicology, physical, and chemical characteristics,
- the particular types of environments likely to be encountered which may be sensitive to these chemicals,
- the non-target organisms likely to be of concern, and
- the data available in the APSAS program upon which calculations could be based.

The chosen MOE's may consist of very simply calculated measures, for example relating the LC_{50} (concentration lethal to 50 percent) of an aquatic species of concern to the concentration expected to be deposited in a 10 inch deep pool of water.

TASK 4: Software Implementations.

When the results of the previous three tasks have been approved by the contracting officer (on the basis on informal reports), the necessary modifications to the APSAS software and coding of additional programming will be performed to enable calculation of the measures of biological effectiveness. Changes and additions to the ASPAS software must be designed to maintian the scheme for interactive data input, program control, and

output. Options for display of the MOE's should include profile graphs, contour displays, tabular output, and summary statistics.

Machine and Language Requirements

In order to maintain consistency and compatibility with the current MOD 0 ASPAS (FSCBG) program, the software produced under this project should be written in FORTRAN for use on the Forest Service UNIVAC computer in Fort Collins, Colorado. All software must be demonstrated on that facility before acceptance by the contracting officer.

Program listings including ample comments will be supplied, along with supporting documentation, describing the programming approach and details of the coding.

Level of Effort

The level of effort required to complete the four tasks is estimated to be 8 man-months.

PROJECT 5: ASPAS Sensitivity Analysis

A sensitivity analysis should be undertaken to determine the influence of changes in input data and parameters on the outputs of the model. This analysis should not be undertaken until the enhancements represented by projects 1 and 4 have been completed, especially the introduction of measures of effectiveness for herbicides and insecticides and the introduction of an explicit measure or measures of environmental hazard, since these outputs would be the most appropriate ones for investigation. This analysis will help the user decide which inputs should receive the most attention. It will also act as a test on perceived priorities during model development. The sensitivity analysis will have to be evaluated in the light of all assumptions that were made during model development, since the technique assumes that the structure and all functional relationships of the model are assumed to be correct. Any conceptual errors present may lead to spurious results (van Keulen, 1976).

A simple perturbation approach (which can make use of analysis of variance techniques, as for example Steinhorst and others, 1977) should be followed, since it can be expected to reveal the most important aspects of the behavior of the system if applied in the region of concern within the parameter space. The analysis should be repeated for several scenarios, representing the most likely situations for application. The parameters should be perturbed singly, and on the basis of those results, in selected combinations. This approach should be relatively economical. Although more complete approaches are available, for example, based on the sensitivity theory of Tomovic (1963, 1970), they are generally unweildy and uneconomical for models of this size. However, prospective contractors should feel free to suggest alternative approaches.

The analysis should be primarily aimed at describing the sensitivity of measures of biological effect (including measures of hazard to non-target organisms, and MOE's for herbicides and insecticides) but some statistics should also be developed on the sensitivity of predictions of deposition at selected points, including ground level.

A final report should be prepared detailing the methodology used, presenting the results, and discussing their implications.

Level of Effort

The total level of effort required to complete the analysis and report is estimated to be two man-months.

PROJECT 6. Documentation of the MOD 1 ASPAS.

TASK 1: Complete System Documentation.

A document will be produced which can serve as a user's manual, reference manual, and programmer's documentation for the ASPAS system. The document should describe all significant model modifications which have occurred since MOD 0, but the document

should be complete in itself. This new documentation will describe a completed generation (MOD 1) of the system, which is ready for general use.

The document should be sufficiently clear and complete to allow a qualified user to correctly operate the system without reference to other sources of information. It should contain an illustrative example problem, a description of the underlying theory, and appendices containing a discussion of the software design, details of its implementation, program listings, and a summary of important results of the sensitivity analysis.

In order to facilities writing of the documentation, the Forest Service will provide a copy of the MOD 0 (FSCBG) program documentation, as well as reports and program listings produced under Projects 1 through 5.

TASK 2: Informational Pamphlet

A simple, smaller document (not to exceed 10 pages) should also be produced for people in the field informing them that the system is available, what it is, and how to make use of it.

Level of Effort

The level of effort required to complete the two tasks is estimated to be three man-months.

MOD 2 DEVELOPMENT

PROJECT 1. Investigation of Modes of Toxicity of Pesticides and Upgrading the Biological Effectiveness Module

TASK 1: Design of Experiments To Determine Modes of Toxicity of Pesticides to Defoliating Insect Species.

Experiments will be designed to determine the toxicity of registered pesticides to three major species of forest defoliating insects: the eastern spruce budworm (*Choristoneura fumiferana*), the Douglas-fir tussock moth (*Orgyia pseudotsugata*),

and the gypsy moth (Lymantria dispar). Specific pesticides to be used in the investigation will be chosen in consultation with the contracting officer, but no more than four chemicals will be used for each defoliating species.

The experiments must be designed to elucidate the relative importance of toxicity resulting from:

- impaction of droplets directly on the insects,
- inhalation of droplets and vapor,
- ingestion of foliage containing the chemical,
- contact of the insect with contaminated foliage, and
- combinations of the above modes.

The first two modes of toxicity (impaction, inhalation) should be studied over a range of conditions of droplet size, air flow, and protection of the larvae by foliage similar to those expected to occur during operational projects. The specific effect of droplet size in particular should be determined.

TASK 2: Carry Out the Experiments

Upon approval of the experimental plan by the contracting officer, the experiments will be performed. A report of the results of the experiments will be prepared, including interpretations and a discussion of implications for mortality prediction models for the ASPAS.

TASK 3: BEM Development: Phase II

Phase II development of the BEM should proceed along a number of fronts with the end objective being the development of a reliable BEM which can be incorporated into future MODs. These different fronts include the following.

- Enhancement of the manner in which factors already accounted for by the Force et al. model are handled.

- Investigation of and possible inclusion of additional factors impacting efficacy.
- Extension of the model to additional pests and pesticides.

These three 'fronts' are discussed in the following paragraphs.

<u>Subtask 1: Improved Detail for Currently Utilized Variables</u>

Each of the variables currently utilized by the Force et al. model uses combined normative/quantitative estimates of likely outcome. To the extent possible these event outcomes need to be expressed quantitatively based upon existing and 'to be generated' data. For example, insecticide dosage estimates are based upon the assumption of 80 percent loss at tree level, and possible events "bracket" this figure. Adaptation of these possible outcomes to receive FSCBG output will result in much more accurate portrayal of dosage. Using FSCBG simulation runs it would be possible to construct probability distributions describing dosage for use by the BEM.

A second factor which should be altered somewhat is the genetic response factor. Studies conducted by Stock and Robertson (1979) on forest defoliators have clearly demonstrated the variations in genetically - mediated response characteristics of these species, both among and within populations. Measurable variations occur between populations over relatively short physical distances. These studies have also demonstrated that genetic response is a key variable in the estimation of target mortality as a function of spray deposit, in fact the model developed by Force et al. includes this as the primary intrinsic factor considered. In utilizing this factor one must first conduct a prespray genetic survey to determine expected response. Through the use of physical simulation (e.g. wind tunnel testing) the expected response of different populations can be estimated

or characterized such that an index of expected response could possibly be substituted for prespray surveys. Such an index would indicate the type of expected population response (e.g. tolerant, susceptible, resistant) for various subgroups within a pest population. Essentially this would entail work almost identical to that conducted in a prespray survey, the difference being that it would be conducted for many populations at the same time via physical simulation. Such advance indications of probable response is necessary if program planning is to be conducted early on.

As already noted, in addition to data on the instar distribution through the population which is already accounted for in the model, more information is necessary concerning the physical distribution of insects throughout the canopy. Pesticide deposition can be expected to vary within the canopy, hence so too will delivered dosage. The implications of this upon target mortality need to be investigated, and if prominent, incorporated into the model.

Finally, any alterations to the model required by the analysis of modes of toxicity under tasks 1 and 2 should be carried out.

Subtask 2: Additional Factor Identification and Analysis.

The Force et al. model currently considers the following variables.

- insecticide dosage,
- genetically determined response characteristics,
- instar distribution
- type of exposure
- moisture condition of the foliage,
- rainfall, and
- presence or absence of larvae.

All additional factors with potentially considerable impact on insecticide efficacy need to be identified and investigated with an objective of determining the <u>relative</u> importance of each. Such additional factors may include: additional details concerning the physical features of both target and host species; factors describing the relationship between target and host species; physical and chemical effects on spray droplets <u>after</u> deposition such as volatilization, photodegradation, etc.; droplet distribution on the leaf surface; temperature effects and others. The objective here is not to develop an inordinately complex model, but rather to develop a probabilistic model which strikes the desired balance between output accuracy and model complexity. Should any of these factors prove to have a substantial effect upon insect mortality they should be incorporated into the model as appropriate. Once so incorporated it would be an easy task to conduct limited sensitivity analysis should be conducted over the factors in an effort to keep the model as simple, yet reliably accurate as possible.

<u>Subtask 3: Extension to Additional Pest Species</u>.

The value of the model, or any model, for incorporation into the ASPAS system necessitates that it be applicable to a variety of pest species. This is of course why a general approach was selected as opposed to a more sophisticated, mathematical model. In its current state the model is applicable to two pest species, the western spruce budworm, and the Douglas-fir tussock only. To be appropriate to future system MODs, capabilities will have to be extended to additional pests. At the present time it would appear best to include two additional species, the eastern spruce budworm, <u>Choristoneura fumiferana</u> and the gypsy moth, <u>Lymantria dispar</u> L. In including additional pest species the principal area of activity is the determination of genetic response for the <u>species</u>. This should not be confused with identification of response variations within a <u>population</u>

discussed earlier. Some indication of the variability of respone expected to occur within these species should also be obtained.

Subtask 4: Software Implementation.

When the results of the preceding tasks have been approved by the contracting officer, on the basis of an informal report, the necessary modifications to the ASPAS software and coding of any additional programming will be performed to implement the upgraded insecticide eficacy model. Changes and additions to the ASPAS software must be designed to maintain the scheme for interactive data input, program control, and output.

Machine and Language Requirements

In order to maintain consistency and compatibility with the current MOD 1 ASPAS program, the software produced under this project should be written in FORTRAN for use on the Forest Service UNIVAC computer in Fort Collins, Colorado. All software msut be demonstrated on that facility before acceptance by the contracting officer. Program listings including ample comments will be supplied, along with the supporting documentation describing the programming approach and details of the coding.

Level of Effort

The level of effort required by these two tasks is estimated to be 18 man-months over a 12 month period.

PROJECT 2. Simplification of Meteorological Input and Improvement of Deposition Predictions.

TASK 1: Simplified Wind Profile Generation.

Description of a complete wind profile through and above a forest canopy requires instrumented towers or sophisticated meteorological gear. A method should be devised to derive wind speed profile estimates from data easily obtainable by field personnel. The output data required by the model could be related to meteorological information obtained from nearby

weather stations and/or some simple wind speed measurements taken on site, along with data describing the stand and topography. The method should be based upon studies already available in the literature e.g. "Some Measurements of the Adiabatic Wind Profile Over a Tall Irregular Forest" (Bergen, 1976) and Vertical Profile of Windspeed in a Pine Stand" (Bergen, 1971).

TASK 2: Simplified σ_A and σ_E Input

The variations in wind direction represented by σ_A (the standard deviation of wind azimuth angle) and σ_E (for the wind elevation angle) are not observable in the field with simple equipment. A method should be devised to estimate these required input data, based on more easily obtainable information. For example, σ_A and σ_E might be estimated from a stability class, which could be derived from simple measurements (which might be obtained from a nearby airport) including the wind speed, wind direction, cloud cover, and time (K. Dumbauld, personal communications).

TASK 3: Persistence and Photodegradation Module.

Certain pesticides, especially some of the biological agents, degrade quite rapidly after being deposited in the field. Degradative processes do not occur equally throughout the canopy, and can even be expected to differ from top to bottom of a leaf. Washoff by rain can of course be an important factor, as well as hydrolysis and other chemical reactions. However, photodegradation is often of primary importance and it is a factor which is expected to vary through the canopy in a fairly predictable way. The amount of sunlight penetrating to different levels in forest canopies has been examined in studies of photosynthesis and energy relationships.

Based on this literature, the stand structure information already required by the model will be used to estimate rates of degradation at various points within the canopy. This

information will be of most use to the module which predicts insecticide effectiveness, and it may help to explain some of the variability in mortality observed with some pesticides.

TASK 4: Deposit Monitoring Data Feedback Routine for Posterior Fitting.

Spray projects typically include some monitoring of spray droplet deposition at least at ground level. For cases when these deposits differ appreciably from what has been predicted by model calculations, a procedure should be designed for the program to allow an adjustment of deposition predictions to account for the discrepancy. This could be a very simple procedure which distributes the observed error within the canopy, assuming that the prediction at the canopy top was correct. This will allow revised estimates of target pest mortality to be made as part of a posterior evaluation.

TASK 5: Software Implementation

When the specific plans for the enhancements developed under Task 1 through 4 have been approved by the contracting officer (on the basis of informal reports) the necessary modifications to the ASPAS software and coding of additional programming will be performed to implement the improvements. Changes and additions to the ASPAS software must be designed to maintain the scheme for interactive data input, program control, and output.

Machine and Language Requirements

In order to maintain consistency and compatibility with the current MOD 1 ASPAS program, the software produced under this project should be written in FORTRAN for use on the Forest Service UNIVAC computer in Fort Collins, Colorado. All software must be demonstrated on that facility before acceptance by the contracting officer. Program listings including ample comments will be supplied along with supporting documentation, describing the programming approach and details of the coding.

Level of Effort

The level of effort required to complete the five tasks is estimated to be 22 man-weeks.

PROJECT 3. Collection of Droplet Spectra Data.

A knowledge of the distribution of droplet sizes produced by a spray system is basic to any attempt to predict spray cloud behavior and fate. This type of data are needed for all sources to be considered by the model, including commonly used types of aircraft spray systems and pesticide formulations. Some of this data is already available due to previous research by groups in the U.S. and Canda. The objective of this project is to extend this base of data to include important equipment and formulations.

TASK 1: Review of Available Data

Review and catalog existing relevant data on droplet spectra. The applicability of this data to droplets of small diameter, ranging down to about 1 micron, should be examined. Much of this data will be made available by the contracting officer.

TASK 2: Choice of Spray Equipment Formulations, and Methodology

In consultation with the contracting officer, the contractor will choose a set of combinations of spray equipment and pesticide formulations for which droplet emissions size spectra are to be determined. The method of data collection and reduction will be outlined in an informal report.

TASK 3: Conduct of Experiments and Final Report

Upon receipt of the contracting officer's approval of the experimental protocol, the experiments will be conducted, relevant data collected and analyzed, and a final report written which summarizes the study methodology and findings.

Level of Effort

The level of effort required by the three tasks is estimated to be 18 man-months over a 12 month period.

PROJECT 4. Additional Foliage Distribution Descriptions.

The stand description input data generation routine developed under a previous project makes the handling of such data easier, and lends itself to the archiving of the necessary data. The program is able to store internally all the information needed to represent the whole range of stand configurations over which the model is to be applied, including hardwood forests and conifers with hardwood understory. This information must be made available to the system. Some of the information is already available in the literature to support this work. For example, Storey (U.S.F.S., Riverside) and perhaps others have developed regression equations for both coniferous and hardood foliage, involving DBH, live crown width, dry foliage weight by height, etc.

The work necessary to collect and organize the data will be undertaken in three stages:

TASK 1: Survey of Available Data.

A survey of the literature will be performed to identify and obtain publications representing relevant studies. A survey of ongoing research should also be made to find any relevant unpublished data.

TASK 2: Develop Stand Classification.

Develop an appropriate stand classification scheme considering the purposes of the ASPAS system and the nature of the available data. An important objective of the classification scheme will be to allow easy use by field personnel. The system should consider species, height, foliage density, stems per acre, and extent of crowns.

TASK 3: Collection and Input of Data.

Identify important data items missing from the literature, and plan the collection of this data in the field. Upon approval of the plan by the project officer, perform the field data collection. Enter in the ASPAS data base the available data from both the literature search and the field studies. The stand description data sets should be clearly identifiable, having been coded according to the classification scheme developed under Task 2.

Level of Effort

The level of effort required for the three tasks is estimated to be 15 man-months over a 9 month period.

PROJECT 5. Development of an Empirical Impaction Model.

The theory of impaction has not been developed sufficiently to accurately represent all of the factors relevant to forest pesticide spray behavior. The inadequacy of Sell's law was made evident during early applications of the FSCBG model (ASPAS MOD 0), so the model was subsequently altered to include an improved but still theoretically based formulation based on the publication by Golovin and Putnam (1962). Even this improved representation of inertial impaction leaves some important factors unaccounted for.

Consequently, impaction could best be predicted based on experimentation. For example, wind tunnel experimenets have been conducted and have generated relevant data. They have been conducted in Canada as well as the U.S., e.g. "Particle Deposition in a Douglas-fir Canopy" by Wedding, Carney, Ekblad, and others (1977), who examined deposition not only on foliage but also on target insect larvae. This kind of approach can account for many of the micrometeorologial effects, electrostatic effects, and surface effects of roughness and adhesion.

Irregular target geometries, such as hair-covered caterpillars would also be accurately reflected by an empirical relationship, although they could not be easily represented theoretically.

The development of the necessary empirical relationships is the objective of the following tasks.

TASK 1: Experimental Design

Experiments will be designed to generate predictive equations describing the imapction of pesticide droplets impinging upon larvae of important forest defoliating insects, and foliage of their common host plants. The experimental conditions regarding the larvae, host plants, and meteorology should be designed to mimic to the extent possible those expected to occur in the field during operational insect control programs. The experiments should be designed to determine effects of wind speed and droplet sizes expect to occur in the field.

Similar experiments should be designed to generate predictive equations describing the impaction of herbicide droplets impinging upon broad leaf species which are common targets of operational programs of herbicide use.

TASK 2: Conduct Experiments and Analyze Results

Upon approval of the experimental protocol by the contracting officer, the experiments will be conducted and the data analyzed. This analysis will produce equations for the prediction of impaction which are suitable for incorporation in the ASPAS system. They may be modifications to the existing models which describe the probability of penetration and inertial impaction, or an entirely different formulation, but they must be consistent with the form and the purpose of the existing ASPAS system.

TASK 3: Software Implementation

When the results of Task 2 have been approved by the contracting officer, on the basis of an informal report, the necessary modifications to the ASPAS software and coding of any necessary additional programming will be performed to implement the new impaction model. Changes and additions to the ASPAS software must be designed to maintain the scheme for interactive data input, program control, and output.

Machine and Language Requirements

In order to maintain consistency and compatibility with the current MOD 1 ASPAS program, the software produced under this project should be written in FORTRAN for use on the Forest Service UNIVAC computer in Fort Collins, Colorado. All software must be demonstrated on that facility before acceptance by the contracting officer. Program listings including ample comments will be supplied, along with the supporting documentation describing the programming approach and details of the coding.

Level of Effort

The level of effort required to complete the three tasks is estimated to be 18 man-months.

PROJECT 6. Mesoscale Model Interface.

TASK 1: Choice of a Model and Determination of Requirements for Alterations and Interface.

The structure of the MOD 1 ASPAS system of models is not adequate for the analysis of long-range drift, although the current system can be used to investigate the magnitude and nature of near-field drift. Long distance drift analysis often requires a consideration of the effects of topography. Mesoscale meteorological models have been developed which are capable of representing topographic effects on a wind flow field at the necessary scale. Some of the applicable models have been

reviewed by Bergen (1979). EPAMS was probably the first model to combine a consistent flow field with a plume model.

An appropriate mesoscale model should be chosen and an interface should be designed to enable an application of the ASPAS to generate data for input to the mesoscale model. This interface could require alterations to either the ASPAS itself and/or the mesoscale model. The mesoscale model itself should also be modified if necessary to produce appropriate measures for environmental hazard estimation.

Where complex terrain effects on cloud trajectory are not important, a simpler model such as that developed by Reid and Crabbe (1980) may be suggested, but the developement of an adequate mesoscale model will likely make the inclusion of a simpler model unnecessary, since level topography can be considered as a special case of the more complicated situation.

The required accuracy of a mesoscale model should be considered separately from that required onsite. In estimating environmental hazards due to drift, it would be preferable to err on the high side. But in estimating the amount deposited on target, it would be preferable to err on the low side. The required accuracy is also probably greatest for on-site deposition. These requirements are consistent with a configuration coupling the ASPAS with a mesoscale model such as EPAMS. However, prospective contractors should feel free to suggest other modeling approaches.

A shortcoming of the ASPAS at present is that all of the chemical which enters the canopy is assumed to remain there. This does not account for evaporation and dispersal of small droplets of the chemical back into the atmosphere. This ventilation effect should be considered as it impacts offsite drift as well as onsite effects.

A report will be written detailing the choice of the mesoscale model and rationale for the choice, and plans for model alterations and interfacing.

TASK 2. Programming and Demonstration

When the results of Task 1 have been approved by the contracting officer, the necessary modifications to the ASPAS or mesoscale model software and coding of any necessary additional programming will be done to enable long-distance drift analyses to be performed based on ASPAS system applications to one or several spray blocks.

Changes and additions to the ASPAS software must be designed to maintain the scheme for interactive data input, program control, and output. An example problem will be analyzed to demonstrate the interface and operation of the mesoscale model.

Machine and Language Requirements

In order to maintain consistency and compatibility with the current MOD 1 ASPAS program, the software produced under this project should be written in FORTRAN for use on the Forest Service UNIVAC computer in Fort Collins, Colorado. All software must be demonstrated on that facility before acceptance by the contracting officer. Program listings including ample comments will be supplied, along with the supporting documentation describing the programming approach and details of the coding.

Level of Effort

The level of effort required to complete the three tasks is estimated to be 6 man-months.

PROJECT 7. ASPAS System Validation.

Validation of the ASPAS model by carefully planned field trials will be a necessity. The testing should be considered in two phases: calibration and validation. Calibration is a

process of fitting the model to observed data. In this phase, relatively poorly known parameters can be adjusted if necessary in order to improve the correspondence of the model with the observed data. Relevant historical data could be used for this purpose, as well as the initial field trials. Subsequently, the model can be truly validated by showing that it can handle independent data under various conditions. The principal objective of the model is to summarize and predict, but the requirements for validation depend on the uses to be made of the predictions. Verification of model outputs must be related explicitly to the purposes of the end users. One purpose of validation should be to demonstrate to potential users of the information that it is superior to subjective techniques.

Validation of the system will require that the following tasks be performed.

- Task 1. Plan field trails for calibration and validation. The conditions should be chosen to represent those expected to be typical of operational aerial spray projects for forest pest management. The plan must be approved by the contracting officer before beginning Task 2.
- Task 2. Conduct calibration trials.
- Task 3. Analyze the data from the trials and on the basis of both that and available data from past applications, adjust model parameters to calibrate the models as well as possible.
- Task 4. Conduct validation trials.
- Task 5. Analyze the data from the validation trials, and report results. A final report should be produced which discusses the expected accuracy of predictions in various situations, and implications for model users with various objectives.

Expected Cost

The cost of this project is expected to be approximately $300,000.

PROJECT 8. Aerial Spray Planning and Analysis System MOD 2 Documentation.

Two documents must be produced. The first will serve the needs of the system users. The second will be for programmers and the system manager. These documents should describe all signficant model alterations which have occurred since MOD 1, but the documents should be complete in themselves. This new documentation will describe a completed generation (MOD 2) of the system, which is ready for general use.

TASK 1: Develop User Documentation.

The user documentation for MOD 2 should be aimed primarily at FPM specialists, although it will probably be used by others also. It should address the theory of the model in a general and easily understandale way, and clearly outline the proper manner of use and interpretation of output of the system. This document should be sufficiently clear and complete to enable a qualified specialist to operate the system without reference to any other sources of information. It should include an appropriate example problem.

TASK 2: Develop System Maintenance Documentation

A document should be produced for the system manager and any analysts and programmers who may be involved in system development or maintenance. It should encompass the theory of the model (in a more complete manner than the user documentation), the overall design of the software system, details of the coding, and listings of the source code.

In order to facilitate writing of the documentation, the Forest Service will provide a copy of the ASPAS MOD 1 documentation, as well as reports and program listings produced under projects one through seven of MOD 2 development.

Level of Effort

The level of effort required for this project is estimated to be six man-months.

APPENDIX D

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS

TABLE D-1

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS

SCOPE

AIRCRAFT

- Fixed Wing
- Rotary Wing 0

TERRAIN

- Flat, level 0
- Sloped 1-9
- Ridges, ravines 10

FOREST STRUCTURE

- Homogeneous, single type
- Homogeneous, mixed types 0
- Terminating at straight edge 1-9
- Terminating at curved edge
- Isolated, curcular interior opening 10
- Irregular interior opening

TREE TYPE

- Conifer 0-1
- Deciduous
- Mixed 2

SPRAY FORMULATION TYPE

- Water based (simple) 0-1
- ~~Oil based~~ 2
- Adjuvants 3-

DROPLET SPECTRUM

- 5 micron and up
- 100-500 micron 0-4
- 0-100 micron 5

METEROLOGY

- Stable across spray block 0-4
- Edge effects 5
- Interior effects (chimneys, etc.) 10

MEASURE

- Deposition 0-1
- Dosage 2-10

VALIDITY

ON-SITE

- Poor
- Fair
- Moderate 0
- Good 1-2
- Very good 3-9
- Excellent 10

NEAR OFF-SITE

- Poor
- Fair 0
- Moderate 1
- Good 2
- Very good 3-10
- Excellent

FAR OFF SITE

- Poor
- Fair 0-1
- Moderate 2
- Good 3
- Very good 10
- Excellent

USER CONVENIENCE

PREPARATION OF INPUTS

- Extensive knowledge and time 0
- Simplified forest stand input
- Simplified spray parameter input 1
- Simplified meteorological input 2

PRESENTATION OF OUTPUTS

- Tabular 0
- Profile plots
- Contour plots 1-10
-

COMPUTER ACCESS

- Remote batch 0
- Interactive 1-2
- Emulation for micro-computer 3-10

TABLE D-2

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS MORTALITY (INSECT PEST OR UNDESIRABLE PLANT SPECIES) MODELS

SCOPE

INSECT PEST

0
- Spruce budworm — 1-4
- Tussock moth
- Gypsy moth — 5-10
- Southern pine beetle

MODE OF ACTION

0
- Unspecified — 1
- Ingestion
- Contact — 2-9
- Inhalation — 10

INSECTICIDE

0
- Carbaryl
- Orthene
- Dylox
- Dimilin — 1
- Bt — 2-10
-

MEASURE OF IMPACT

0
- Relative index (heuristic)
- Mortality estimate (point) — 1
- Probabilistic mortality — 2-5
- Weakening — 6-10

UNDESIRABLE PLANT SPECIES

0
- Broadleaf — 1
-
-

MODE OF ACTION

0
- Unspecified — 1-4
- Systemic
- Defoliant — 5
-

HERBICIDE

0
- 2, 4, 5-T — 1
- 2,4-D
- Triclopyr
-

MEASURE OF IMPACT

0
- Relative index (heuristic) — 1
- Percentage defoliation — 2-4
- Percentage mortality - count
- Percentage mortality - mass — 5-9
- Growth loss - months — 10

VALIDITY

ON-SITE

0
- Poor
- Fair — 1
- Moderate — 2-4
- Good — 5-9
- Very good — 10
- Excellent

NEAR OFF-SITE

0
- Poor
- Fair — 1
- Moderate — 2-4.
- Good — 5-9
- Very good — 10
- Excellent

USER CONVENIENCE

PREPARATION OF INPUTS

0
- Extensive knowledge and time — 1
- Simplified input — 2

PRESENTATION OF OUTPUTS

0
- Tabular
- Profile plots
- Contour plots — 1-5

COMPUTER ACCESS

0
- Remote batch
- Interactive — 1-2
- Emulation for microcomputer — 3

TABLE D-3

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS PEST POPULATION DYNAMICS AND FOREST STAND RESPONSE MODELS

SCOPE

INSECTS

	0-4
Spruce budworm	5
Tussock moth	6
Gypsy moth	7-10
Southern pine beetle	

FACTORS EXPLICITLY ADDRESSED

	0-4
Unspecified	5-7
Feeding	
Temperature	
Humidity	8
Migration	9
Parasitism	10
Genetics	

MEASURE OF RESPONSE

	0-4
Population	5-9
Health indices	10

FOREST COMPOSITION

	0-4
Spruce-fir	5
Douglas-fir types	6
Mixed hardwood types	7
Other major types	8-10

FACTORS EXPLICITLY ADDRESSED

	0-4
Soil quality	
Water	
Defoliation	5-10
Fire	
Insects - subsequent attacks	

MEASURES OF RESPONSE

	0-4
Direct mortality	
Loss of growth	5-10
Susceptibility to disease	
Increased fire hazard	

VALIDITY

ON-SITE

	0-4
Poor	
Fair	5-7
Moderate	8
Good	9
Very good	10
Excellent	

NEAR OFF-SITE

	0-4
Poor	
Fair	5-7
Moderate	8
Good	9
Very good	10
Excellent	

FAR OFF-SITE

	0-9
Poor	
Fair	10
Moderate	
Good	
Very good	
Excellent	

USER CONVENIENCE

PREPARATION OF INPUTS

	0-4
Extensive knowledge and time	5
Simplified forest stand input	
Simplified pest biology input	7

PRESENTATION OF OUTPUTS

	0-4
Tabular	5
Profile plots	8
Contour plots	10

COMPUTER ACCESS

	0-4
Remote batch	5-7
Interactive	8-10
Emulation for microcomputer	

TABLE D-4

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS
FOREST USE AND ECONOMICS MODELS

SCOPE

USES

0-9
- Pulp wood
- Lumber
- Recreation

10

SILVICULTURAL FACTORS

0-9
- Growth and harvesting
- Salvage operations
- Alternative stands

10

ECONOMIC FACTORS

0-9
- Market trends
- Economies of scale

10

VALIDITY

ON-SITE

0-9
- Poor
- Fair
- Moderate
- Good

10
- Very Good
- Excellent

NEAR OFF-SITE

0-9
- Poor
- Fair
- Moderate
- Good

10
- Very Good
- Excellent

USER CONVENIENCE

PREPARATION OF INPUTS

0-9
- Extensive knowledge and time

10
- Simplified input
-

PRESENTATION OF OUTPUTS

0-9
- Tabular

10
- Profile plots
- Contour plots

COMPUTER ACCESS

0-9
- Remote batch
- Interactive

10
- Emulation for micro-computer

TABLE D-5

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS AERIAL SPRAY MISSION COSTS MODELS

SCOPE

FACTORS

- Aircraft
- Pesticide
- Total acreage
- Block size distribution
- Delivery constraints — 0-10

COST BREAKDOWN

- Aircraft
- Personnel
- Pesticide
- Ferrying
- Accomodations — 0-10

VALIDITY

ON-SITE

- Poor
- Fair
- Moderate — 0-9
- Good
- Very good — 10
- Excellent

USER CONVENIENCE

PREPARATION OF INPUTS

- Extensive knowledge and time — 0
- Simplified input — 1

PRESENTATION OF OUTPUTS

- Tabular — 0

COMPUTER ACCESS

— 0
- Remote batch
- Interactive — 1-2
- Emulation for micro-computer

TABLE D-6

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS ENVIRONMENTAL MODELS

APPLICABLE AREA

- On-site — 0
- Near off-site — 1
- Far off-site — 2-10

FACTORS CONSIDERED

- — 0
- Fisheries
- Streams — 1-6
- Endangered species
- Agent persistence
- Biomagnification — 7-10

MEASURE OF IMPACT

- Deposition — 0-1
- Dosage — 2-10

CONSTRAINT

- Deposition — 0-9
- Dosage — 10
- Non target species mortality

ON-SITE

- — 0
- Poor
- Fair
- Moderate — 1-10
- Good
- Very Good
- Excellent

NEAR OFF-SITE

- — 0
- Poor
- Fair
- Moderate — 1-10
- Good
- Very good
- Excellent

FAR OFF-SITE

- — 0-1
- Poor
- Fair
- Moderate — 2-10
- Good
- Very good
- Excellent

PREPARATION OF INPUTS

- Extensive knowledge and time — 0
- Simplified input — 1

PRESENTATION OF OUTPUTS

- Tabular — 0
- Profile plots
- Contour plots — 1-10

COMPUTER ACCESS

- — 0
- Remote batch
- Interactive — 1-2
- Emulation for microcomputer

TABLE D-7

POTENTIAL ATTRIBUTES AND CAPABILITIES OF ASPAS FOREST AND FOREST PEST MANAGEMENT MODELS

SCOPE

FACTORS	
	0-4
• Pest suppression	
• Harvesting	5-9
• Budget constraints	
• Recreation	10
• Fire	
• Forest composition	
• Forest succession	

TYPE OF FOREST	
	0-4
• Commercial software	5
• Commercial hardwood	6
• Orchard or nursery	7-9
• Private, residential woods	10

DECISIONS FORECAST	
	0-4
• Pesticide treatment	
• Herbicide treatment	5
• Harvesting	7-8
• Regeneration	
• Parasite introduction	10

VALIDITY

ON-SITE	
	0-4
• Poor	
• Fair	5-7
• Moderate	8-9
• Good	10
• Very good	
• Excellent	

NEAR OFF-SITE	
	0-4
• Poor	
• Fair	5-7
• Moderate	8-9
• Good	10
• Very good	
• Excellent	

USER CONVENIENCE

PREPARATION OF INPUTS	
	0-4
• Extensive Forest stand input	5
• Simplified forest stand input	
• Simplified management input	6

PRESENTATION OF OUTPUS	
	0-4
• Tabular	5-8
• Profile plots	9
• Contour plots	10

COMPUTER ACCESS	
	0-5
• Remote batch	6
• Interactive	7-9
• Emulation of micro-comput[illegible]	10

curve fitting techniques using existing or generated data. Other approaches, one of which is described herein, combine some of the above methods thereby taking advantage of the most desirable attributes of each.

As already noted, very few attempts have been made in terms of modeling, or predicting pesticide efficacy. In terms of mathematical simulation models, apparently the only insect pest so modeled is the cotton boll weevil, Anthonomus grandis Bohemin (Jones et al. 1977). As pointed out by Force et al. (unpublished) this model is not applicable to defoliating insects. Mathematical simulation has been discarded from further consideration for relatively pragmatic reasons. First, as noted, modeling of pesticide efficacy, e.g. target pest mortality, is an extremely complex issue. The time and cost of such development would be prohibitive, particularly given the objectives of the ASPAS system. Also in keeping with ASPAS objectives, mathematical simulation simply does not allow the degree of flexibility required by advance program planning. The BEM objective is to provide a relatively simple, accurate estimation of pest mortality for a variety of species. The mathematical simulation approach was deemed too rigid (e.g. separate models would likely have to be developed for each species) to meet these objectives.

At the other end of the spectrum in terms of simplicity is the use of regression analysis to estimate mortality. Such an approach has been demonstrated by Young (1978) using spruce budworm spray project data. The objective here is to interpret the relationship between target mortality and spray deposit parameters such as droplets/cm^2, vmd, and mass. This particular approach does in fact enable one to analyze the effect of variations in spray deposit upon mortality, however, it was deemed inappropriate for an ASPAS system for two principal reasons. First, it relies very much upon the existence of control program data from past efforts. The more specific such data is

to the problem at hand, the greater is the estimation accuracy and hence contribution to proram planning. Generally speaking, such information is not readily available for a large variety of situations. The second and very closely related reason is that it does not attempt to (indeed it cannot) account for any intrinsic factors affecting mortality or most extrinsic factors. Given that the effect of such factors varies widely over different settings, statistical influence would provide mortality estimates which were subject to a great deal of doubt, and hence incompatible with ASPAS objectives. This approach may in fact provide useful in terms of planning follow-up treatments over areas where initial treatment (planned using ASPAS) has not been completely effective. As already noted, the regression method described by Young is useful in analyzing the effect of variations in spray deposit upon mortality. In situations where only application parameters can be deemed to be the cause of loss of spray efficacy, regression analysis would in fact be a useful decision making tool.

Finally, as a mid-spectrum alternative, the use of a probabilistic approach has been examined. An example of such an approach is that described by Force et al. (unpublished) where a probability model of insecticide efficacy is discussed. The model is a deterministic one which uses probability theorems to integrate the effects of a number of intrinsic and extrinsic factors. Included are the effects of:

- insecticide dosage,
- genetic response,
- instar distribution,
- type of exposure,
- moisture conditions,
- rainfall following spray, and
- presence or absence of larvae at time of spray.

The main attraction of this approach is the fact that it attempts to account for various intrinsic and extrinsic factors affecting mortality, and yet is still a relatively simple, flexible approach. In tests using spray program data for both the western spruce budworm, Choristoneura occidentalis (Freeman), and the Douglas-fir tussock moth Orgyia pseudotsugata (McDunnough), the method has also proven quite accurate. The recommended approach for BEM development discussed in the next subsection is based upon the Force et al. approach. Enhancements and modifications necessary to bring the model in line with ASPAS objectives are discussed in detail in that subsection.

3. Recommended Development Approach

The general approach recommended involves two phases; the development of simplified stochastic BEM for near term use, and the subsequent development of a more sophisticated and generally applicable BEM for incorporation into future MODs. Based upon the description given in the foregoing sections, the recommended approach utilizes and builds upon the model described in Force et al. (unpublished). That particular approach attempts to account for a number of the many intrinsic and extrinsic factors which affect target pest mortality. The model is a deterministic one which utilizes probability theory to account for these factors. The objective of Phase I involves making few relatively minor enhancements to the Force et al. model such that it is suitable for incorporation into the MOD 1 system. The objective of Phase II is to build upon the model in order to develop a BEM which better suits the purpose and objectives of the ASPAS system in terms of accuracy, applicability to a variety of situations (robustness), and compatability with other ASPAS components. The principle steps inherent in Phase II are to first conduct basic research (described below) aimed at identifying and evaluating factors impacting pesticide efficacy, second to extend the model's applicability to more situations, again through basic

research as described below, and finally to incorporate such information into the model itself. The specifics of this general approach are given in the ensuing sub-sections. It should be noted that Force et al. also have recognized the possibilities associated with developing a stochastic model which integrates the effects of additional variables, both intrinsic and extrinsic.

3.1 BEM Development: Phase I

We have already noted that the objective of the Phase I BEM development is to provide a near term method for estimating expected pesticide efficacy. With relatively minor enhancements it would appear as though the Force et al. model well suits this objective in its current state, relative to the two insect species for which the model was developed, and to plant species receiving herbicide treatment. Focusing first upon insecticide treatments, the principal model alteration recommended is to provide the capability of outputs to be expressed in terms of a probability distribution. Such a change will allow greater flexibility in program planning and decision-making. It will allow for the calculation of marginal costs and benefits caused by changes in application parameters via the insecticide dosage variable. A simple procedure whereby percent mortality estimates are grouped into classes of a given width, with each class described by an associated probability of occurence, would very likely be the most desirable.

A second area of short term enhancement involves making the model applicable to a number of different heights within the canopy simultaneously. Estimates of mortality for different heights are necessary in the determination of objective droplet size which is a factor greatly influencing many application characteristics, particularly canopy penetration, deposition, drift hazard minimization, and, of couse, target mortality. In